Kass Green & Associates

Redfish Bay Texas
Airborne Sensor Comparison and Propeller Scar Mapping
Final Report

by

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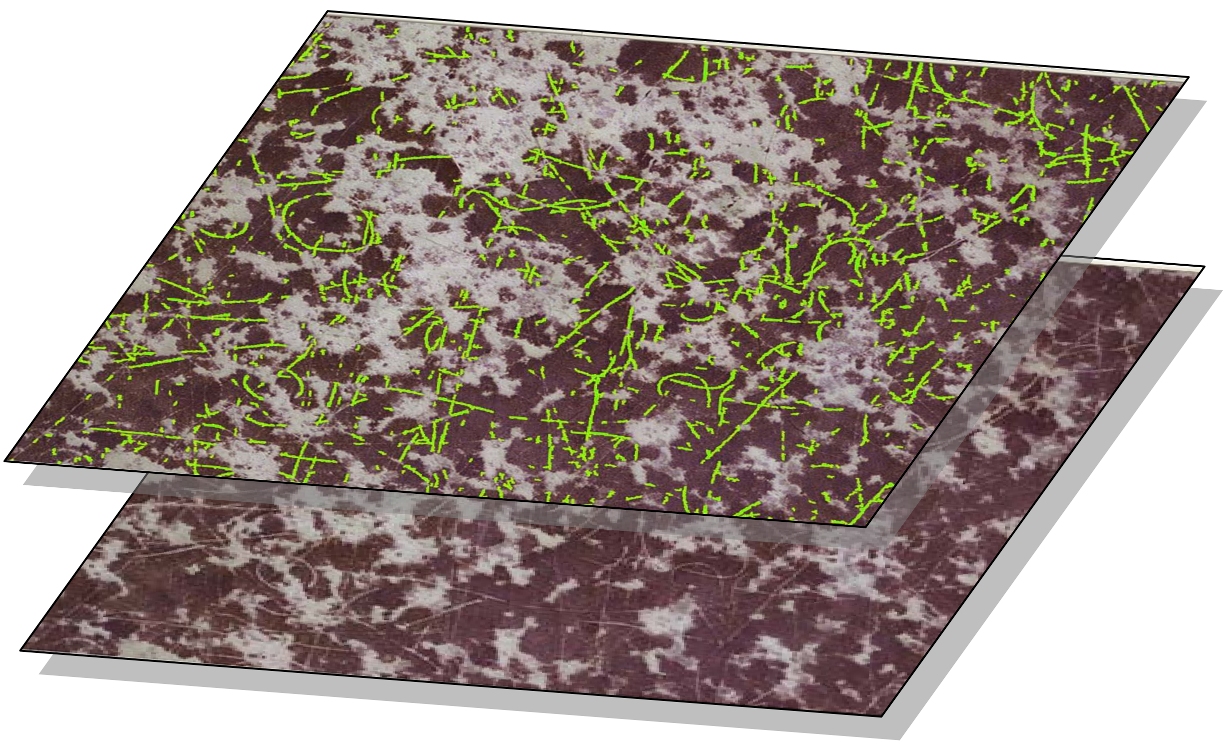

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Acknowledgements

Completion of this project required the dedicated effort of many people. The authors would like to especially thank Dennis Pridgen of the Texas Parks and Wildlife Department who carefully monitored Texas environmental conditions to ensure outstanding and stable weather and tidal conditions for the imagery collects. Dennis also spent countless hours in the field, patiently teaching us about Texas benthic habitat and the impacts of propeller scars. Other Texas Parks and Wildlife Department personnel critical to the success of the project include Jim Simmons, Faye Grubbs, and Ashley Summers. John Wood of the Texas A&M Harte Research Institute for Gulf of Mexico Studies contributed to the project in many ways. We are particularly grateful for John's construction and deployment of the submerged targets. NOAA personnel Chris Robinson and Bill Stevenson provided instrumental input at different stages of the project. We also are indebted to the imagery reviewers, Chad Lopez of Fugro Earthdata, Keith Paterson and Daniel Bubser of Avineon, Chris Barnard of the Office of Homeland Security, and Pasquale (Pat) Scaramuzza, Michael J. Choate and Jon Christopherson of USGS. George Lee and Greg Stensaas of USGS were also extremely helpful in clarifying the common criteria used to evaluate digital airborne imagery. The system manufacturers, Intergraph, Microsoft, and Leica, were always gracious, answering countless questions and providing details about their systems. Finally, we would like to thank the sensor operators, Sanborn Map Company, Photo Science, and Fugro Earthdata for the high standards of their work, their professionalism, and their willingness to work together to enable all the imagery to be collected on the very best day.

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Executive Summary

This report compares the use of DMC, UltraCam and ADS40 digital airborne camera imagery for mapping benthic habitat and identifying boat propeller scars in seagrass habitats. Image data from all three sensors were collected over Redfish Bay, Texas on the same day, under almost identical environmental conditions. Redfish Bay is unique for the richness of its benthic habitat, and for ongoing research focused on inventorying and monitoring the resources of the Bay. Following collection of the imagery, the data sets were compared to one another for spectral response, edge detection, and spatial accuracy. Next, experts in thematic mapping qualitatively reviewed the three imagery sets for suitability for benthic habitat mapping. Finally, automated methods were used to create maps of propeller scars from each data set and the accuracy of each map was analyzed.

Significant findings of the project are

- Propeller scars comprise less than 1% of the area of Redfish Bay, but are ubiquitous throughout the shallow areas of the Bay, significantly fragmenting seagrass beds.
- Digital airborne UltraCam, ADS40-52, and DMC imagery can be used to effectively map benthic habitat and propeller scars.
- The spatial accuracy of all three sensors greatly exceeded contract standards, with the DMC having the highest spatial accuracy.
- Spectral separatability of benthic habitat class and propeller scars is best in the DMC and the ADS40-52 imagery.
- Propeller scar maps produced from the ADS40-52 imagery were significantly more accurate than those produced from the DMC or UltraCam imagery; and propeller maps produced from the DMC imagery are significantly better than those produced from the UltraCam imagery.

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I. Project Overview

The coast of Texas supports a wide diversity of marine habitats, provides an abundance of recreational opportunities, and contributes significantly to the Texas economy. Dominated by submerged seagrass meadows, the bays provide essential nursery habitats for estuarine fisheries and support a wide variety of wildlife and marine life including shrimp, crabs, juvenile game fish, sea turtles, shorebirds, and waterfowl (TPWD, 2008a). They also function as critical source of organic biomass, and act to stabilize coastal erosion and sedimentation (TPWD, 2008b).

Over the last 30 years, the bays have been significantly impacted by human activity. The population of coastal Texas is growing at 2-3% per year, accompanied by increased shoreline development and recreational use. Managing and protecting this diverse and sensitive resource requires knowledge of the state's coastal marine habitat distribution and an understanding of the causes of change in these habitats over time.

Numerous studies have documented an alarming loss of seagrass habitat throughout the southern Texas Gulf Coast (Pulich et. al. 2003). Of special concern is the impact of boat propeller scars on seagrass beds. Propeller scars (pictured in Figure 1) are defined by the State of Texas as, "a trench cut into the bay bottom by a propeller that cuts the roots and rhizomes of the seagrass plant loose" (TWPD, 2008c). A 1990's report by the Corpus Christi Estuary Program documented a link between boat traffic and degradation and fragmentation of seagrass beds (TWD, 2004). By 2005, a sample of 2 linear miles of Redfish Bay showed that half of the area sampled was impacted by propeller scars (TWPD, 2008d). As described by the Texas Division of Parks and Wildlife, "When propellers cut through the bottom, they destroy the roots of the seagrasses, and it can take years for the scars to heal, particularly in turtle grass beds. Some prop scars channel currents and can become many times wider and deeper than they initially were" (Reed, 2006).

Much of the concern about prop scar impact has been focused on Redfish Bay, a 62 square mile area located just north of Corpus Christi, Texas and displayed in Figure 2. In an effort to reduce propeller scars, the Seagrass Task Force supported voluntary restrictions on boating in Redfish Bay in 2000, and in 2004 the State adopted "regulations prohibiting the destruction or up rooting of seagrass in Redfish Bay"(TPWD, 2008d).

Figure 1. Oblique view of propeller scars in turtle grass as seen from a boat (TPWD, 2006e).

To better understand the impact of propeller scars on seagrass beds, NOAA's Coastal Services Center (CSC), the Texas Parks and Wildlife Department (TPWD) and Texas A&M University Center for Coastal Studies cooperated in a study to examine propeller scars in the seagrass habitat of Redfish Bay. Redfish Bay was chosen because of its recognized critical benthic habitat, low tidal variability, and quality of research data available. The study is the first attempt to comprehensively map the size and number of scars within the bay. The map produced for the study allowed for eventual quantitative monitoring of propeller scar impacts.

NOAA chose Fugro EarthData, Inc. and Kass Green and Associates to map propeller (prop) scars using three concurrently captured digital airborne image data sets. The goals of the project were to

1. Document differences between the three airborne multi-spectral imagery sensors.
2. Document each sensor's suitability for mapping propeller scars and benthic habitat features, and
3. Develop recommendations for future benthic mapping efforts.

Achievement of these goals required:

1. Near simultaneous capture of ADS40-52, DMC and UltraCam digital airborne data over Redfish Bay during prime weather, water and tidal conditions[1].
2. Analysis of the three image sets to assess the capability of each for use in benthic habitat mapping.
3. Automated image classification of the three image data sets to create three polygon maps of prop scars larger than 1 by 4 pixels
4. Preparation of a peer review quality paper documenting Tasks 1 through 3[2].

This report presents the results of this study and is organized as follows.

Section II compares the technical characteristics of the three sensor systems.

Section III presents the contract specifications for the image collections and describes the actual environmental and other conditions during the capture.

Section IV reviews the quantitative and qualitative evaluations of the three image data sets.

Section V summarizes the methods employed to create the propeller scar maps and presents an analysis of each map's accuracy.

Section VI summarizes the findings of the project and makes recommendations for the use of airborne digital multispectral imagery for future use in benthic habitat studies.

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[1] Fugro-EarthData captured only the ADS40-52 data. NOAA contracted directly for the capture of the DMC and UltraCam data.

[2] An additional task to construct and implement a crosswalk from Fugro Earthdata's Coast Texas benthic mapping project (Green and Lopez; 2007) was later postponed in favor of more investigation into mapping guidance for the Coastal and Marine Ecological Classification Standard (CMECS).

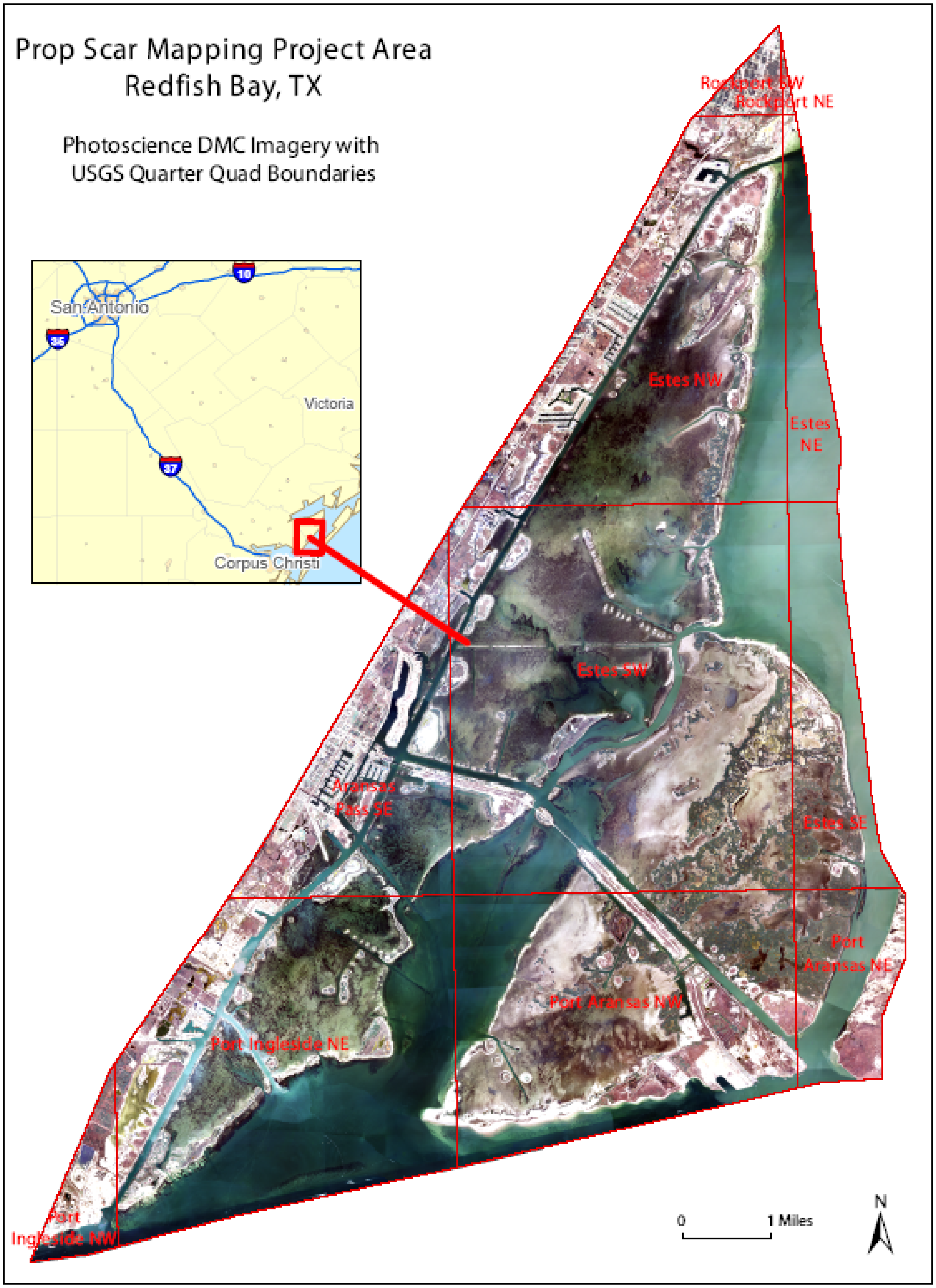

Figure 2. Study area location.

II. Technical Specifications of the Three Digital Camera Sensors

Three different airborne sensors were used to collect digital imagery over Redfish Bay for this project;

- the Leica (www.leica-geosystems.com) ADS40-SH52 operated by Fugro-Earthdata, Inc. (www.Earthdata.com) ,
- the Microsoft UltraCam[3] (www.microsoft.com/ultracam/) operated by Sanborn (www.Sanborn.com) , and
- the Intergraph Digital Mapping Camera (DMC) (www.intergraph.com) operated by PhotoScience (www.PhotoScience.com) .

While over 20 different types of digital airborne sensors are used in remote sensing and photogrammetry, the above three family of sensors have the biggest share of the large format market worldwide.

Table 1 compares the three sensors' capabilities to one another. The sensors differ from each other in multiple ways, but the most significant differences are:

1. The DMC and the UltraCam are framing camera sensors. Framing cameras capture a rectangular portion of the earth visible in the sensor's instantaneous field of view (IFOV) during exposure. The frame of each image is captured rapidly as the aircraft moves forward along its flightline, exposing a matrix of CCD's which register the intensity of electromagnetic energy received by each pixel in each camera band of the sensor. The intensity level is instantaneously digitized, moved off of the array, and stored on a hard drive, allowing the CCD array to quickly capture another image. Both the DMC and the UltraCam have 8 framing camera heads in each system; four to capture panchromatic data at a high spatial resolution, and four to collect multispectral data at a lower spatial resolution. Both the DMC and the UltraCam sensors capture multispectral imagery by using different camera heads with filters for collecting imagery in the red, green, blue, and near infrared wavelengths. The challenge of this type of a sensor is the co-registration of the images from the different cameras to

[3] After the imagery was collected for this project, Microsoft released the UltraCamX, with updated capabilities and new lenses.

produce one multispectral image that can be accurately terrain corrected and geo-referenced for map making.

2. The ADS40 is composed of along track scanners (also called push broom scanners) which rely on a linear array of CCDs to sense lines rather than a rectangle of data. Along track scanners use a dispersing element to split apart the incoming beam of electromagnetic energy into distinct portions of the electromagnetic spectrum to enable the creation of multispectral imagery. The dispersing element eliminates the need for multiple cameras.
3. The DMC and the UltraCam panchromatic cameras collect data at a higher spatial resolution than their multispectral cameras. The multispectral data can then be "pan-sharpened" to bring it to the spatial resolution of the panchromatic data. Conversely, the ADS40 collects panchromatic and multispectral data at the same spatial resolution. In this project the DMC and UltraCam multispectral data were pan-sharpened.
4. The portions of the electromagnetic spectrum captured by the DMC and UltraCam overlap on the borders of the three visible bands; with the UltraCam also having overlap between the red and the infrared bands. Conversely, there is no band overlap in the ADS40-52.
5. The DMC and the UltraCam panchromatic cameras sense energy from the blue to the infra portion of the electromagnetic spectrum. The ADS40-52 panchromatic sensor only sensed energy in the visible bands.

Table 1. Comparison of the technical characteristics of the ADS40-52, UltraCam, and DMC sensos.

	UltraCam	*ADS 40-52*	*DMC*
Sensor/Image Characteristics			
Operation	Frame grabbing	Linear array pushbroom	Frame grabbing
Image Capture	8 camera heads	12 linear pushbroom sensor heads	8 camera heads
Smallest Ground Sample	2.7 cm panchromatic at 1,000 feet above ground	5 cm panchromatic & multispectral at 1,500 feet above ground	3 cm panchromatic at 1,000 feet above ground
Panchromatic Spectral Resolution	380-720nm	465-680nm	400-950nm
MultiSpectral Spectral Resolution			
blue	380-580nm	428-492nm	400-580nm
green	480-640nm	533-587nm	500-650nm
red	580-700nm	608-662nm	590-675nm
infrared	680-940nm	833-887nm	675-850nm
Radiometric Resolution	12+ bit, 14 bit ADC, 16 bit storage	12 bit (16 bit A/D converter and Data channel)	12 bit
Array Size	11,500 x 7,500 pixels (after pan/MS fusing)	12 lines x 12,000 pixels across track	13824 pixel x 7680 pixel (after pan/MS fusing)
Camera System Details			
Lens	Schneider-Kreuznach lenses	Leica DO64 telecentric and temperature stabilized lens	customized Zeiss lens and shutter design
Field of View	55/61° (cross track, along track)	64° across track	69.4° across flight line, 42° in flight direction
Focal Length	100 mm (Pan), 28 mm (MS)	62.5 mm	120 mm
F-Stop	f/5.6 (Pan), f/4 (MS)	fixed at f/4	f/4 to f/22
Shutter	1/500 to 1/60	Not required in line sensors	1/50 to 1/300
Aspect Ratio	11.5:7.5		1.75:1
Frame Rate	1/1.3 frame per second	NA	2.1 seconds per image
Pixel Size	9 micrometers		12 micrometers
Other Specifications			
Sensor Manufacturer	Microsoft	Leica	Intergraph
System Operator for this Project	Sanborn Map Company	Fugro-Earthdata	PhotoScience
Storage	1.5 terabytes (2700 images)	Capacity of mass memory: 0.9 terabytes (exchangeable in-flight)	336 gigabytes (1200 images), can be exchanged during flight
Weight	~110 kilograms for whole system	220 kilograms for working system in the aircraft	80 kilograms main camera, 170 kg complete system
Forward Motion	Yes	Not necessary, inherent in the line sensor principle	Yes, full electronic using TDI
Gyro Stabilized Mount	Yes	Yes	Yes
Co registration of Composite	Image fusion matching	Yes, uses Tetrachroid beam splitter	Sub-pixel image fusion matching

III. Imagery Specifications, Collection and Delivery

To maximize the usefulness of the airborne digital imagery for benthic habitat and propeller scar mapping, NOAA placed stringent conditions on the imagery collection. To minimize differences between the image collections due to environment (rather than due to sensor system technical characteristics), NOAA specified that all image collections occur on the same day and within hours of one other. NOAA's (NOAA, 2006) required environmental conditions were

- Season of Collection: The imagery was to be collected during the Fall of 2006.
- Water Turbidity: Imagery was to be acquired when turbidity was low and collection was prohibited following heavy rains or persistent strong winds.
- Tidal Stage: Imagery was to be collected within 2 hours of the lowest tide, but extreme low tide was preferred.
- Wind and Surface Waves: The absence of wind or waves was preferred. Low wind was acceptable as long as it remained under 10 mph.
- Sun Angle: Sun angles of 30° were optimal and sun angles above 50° were unacceptable.
- Clouds and Haze: Imagery was not to be collected in conditions of excessive clouds, cloud shadows, and/or haze.

NOAA's Texas partners were tasked with monitoring local environmental conditions and determining the day that the image collection flights would occur.

NOAA also specified technical standards for the imagery as follows:

- The horizontal spatial accuracy was required to be within +/- 5 meters CE95 of position on the ground and each contractor was required to provide a spatial accuracy assessment report indicating how this specification was met.
- The radiometric resolution of all image composites was set at 8-bits.
- The imagery was to be processed to remove atmospheric effects such as haze and to highlight the spectral response of submerged areas. Other image processing or enhancements were to be described and reported in the image metadata.

- NOAA specified minimal exposure variation between adjacent flight lines.
- Image sets were to be tiled according to the existing USGS digital ortho quarter quad boundaries with an approximate 100 meter buffer around each tile to prevent gaps in coverage.
- The ground spatial resolution of the imagery was set at 0.25m x 0.25m.
- The imagery was to be delivered in a Universal Transverse Mercator – Zone 14 projection using the NAD1983 datum.
- Spatial offsets between any bands or between either the CIR or RGB composites were restricted to 1 pixel.
- The imagery was to be delivered in GeoTiff format.
- Each image was required to be accompanied by an ESRI compatible pyramid layer or reduced resolution file, typically an .aux file.

Following the project kick off meeting with NOAA and Texas partners, NOAA changed the collection period from the fall to a window from November to February, when the Texas coast experiences winter low tides which are of minimal range and typically 14 inches lower than tides at other times of the year. Adverse weather conditions made image collection undesirable until February 16, 2007 when all three image collections occurred between 11:00AM and 3:00PM. Dennis Pridgen of the Texas Parks and Wildlife Department carefully monitored local weather conditions with the intent of initiating the collections during a short window of clear, still weather that usually follows a Northern cold front which “locks” high pressure over Corpus Christi Bay as illustrated in Figure 3.

Weather conditions on the day of the collection were close to optimal with visibility of 10 miles and clear skies resulting from the passage of a cold front the previous day with a high pressure dome passing over the area. However, during the collections, wind speeds ranged from 8 to 13 miles per hour which exceeded the desired speed of 0 to 5 miles per hour. Table 2 presents the Redfish Bay weather conditions for February 16,

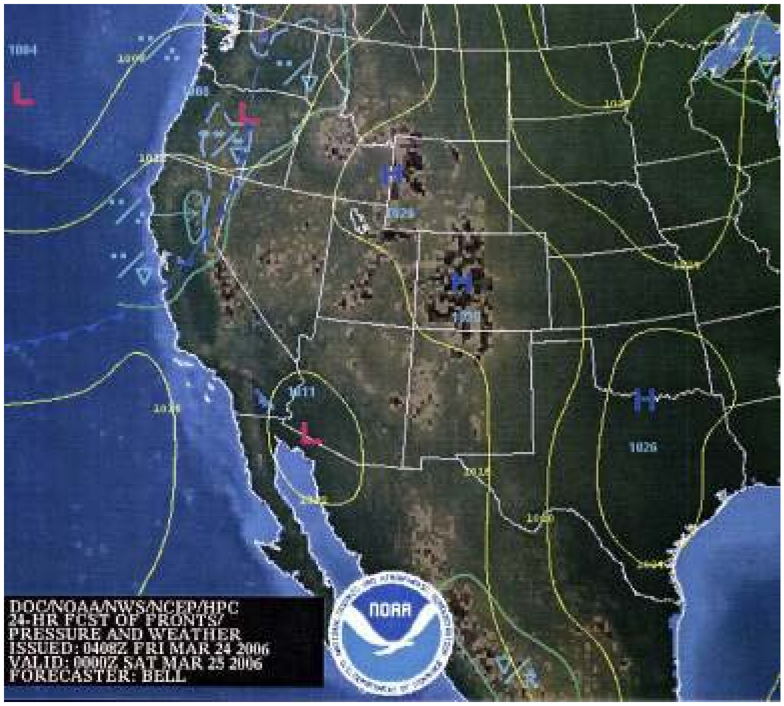

Figure 3. Desired project weather conditions indicating a high pressure zone over the central coast of Texas (figure courtesy of Dennis Pridgen, TPWD).

2007. Water clarity was very good, with Secchi Disk Visibility exceeding 1.5 meters throughout the area[4]. Tides were very low due to north winds over the previous 24 hours having pushed water out of the bays and away from the gulf beaches During the collections, Redfish Bay tidal change was less than 2 inches (as measured at the Rockport Station) ranging from -0.93 to -0.74 feet as displayed in Figure 4. Considering the complexity of environmental variables possible, conditions were remarkably similar for all three image collections.

Table 3 compares the contract standards for environmental conditions and imagery specifications versus those for each actual image collection. One of the goals of the project was to evaluate the imagery for benthic habitat and propeller scar mapping. Therefore, raw frames of data were not acceptable, and some processing of the imagery was required by each operator. As the table indicates, each image set was delivered in a different format. Since the purpose of the project was to compare the effectiveness of

[4] The submerged aquatic vegetation habitats of interest were for the most part located in areas less than 1.2 meters deep.

several sensors for mapping prop scars and benthic habitat, minimal reprocessing was applied to the delivered imagery to bring all three image data sets into a standard format. Depending on the image data set, standardization required some combination of the following: stacking bands so the image was four-banded (R, G, B & NIR), rescaling from 16-bit to 8-bit radiometry, and merging tiles or quarter-quarter quads into quarter quads. Table 4 provides a summary of the reprocessing steps. The net result of reprocessing was that each tile of each image data set had the same spatial, spectral, radiometric resolution and an identical footprint.

IV. Quantitative and Qualitative Review of the Imagery

Following reprocessing, the image data sets were quantitatively compared to one another and qualitatively reviewed by photogrammetry and benthic mapping specialists. Quantitative analysis included evaluation of the imagery

- Spatial accuracy
- Histograms per band
- Edge response, and
- Bi-spectral plots of benthic habitat classes

General and specific qualitative evaluation of the image data sets for mapping benthic habitats was performed by three benthic mapping professionals; Keith Paterson and Daniel Bubser of Avineon, and Chad Lopez of Fugro Earthdata. General evaluation of the imagery was also performed by Chris Barnard of the Office of Homeland Security and Pasquale (Pat) Scaramuzza, Michael J. Choate, Jon Christopherson of the USGS EROS Data Center.

Overall, all three image sets are outstandingly beautiful. Their excellence is perhaps best stated by a USGS reviewer, “All of these instruments are very clean and produce excellent qualitative images. The artifacts found are very minor, and should not impact the immediate use of any data” (USGS, 2007). Figures 5-7 show a sample of each image set captured over the same area in Redfish Bay.

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final) HOURLY OBSERVATIONS TABLE ARANSAS COUNTY AIRPORT (12972) ROCKPORT , TX (02/2007)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 25 ft. above sea level
Latitude: 28.084
Longitude: -97.046
Data Version: VER2

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
						(F)	(C)	(F)	(C)	(F)	(C)											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
16	0053	12	CLR	10.00		36	2.2	32	0.1	26	-3.3	67	10	030		30.42			30.44	AA		30.44
16	0153	12	CLR	10.00		35	1.7	31	-0.5	24	-4.4	64	9	020		30.43			30.46	AA		30.45
16	0253	12	CLR	10.00		34	1.1	30	-0.8	24	-4.4	67	8	010		30.43	0	012	30.45	AA		30.45
16	0353	12	CLR	10.00		34	1.1	30	-1.0	23	-5.0	64	9	010		30.43			30.46	AA		30.45
16	0453	12	CLR	10.00		32	0.0	29	-1.7	23	-5.0	69	7	360		30.44			30.46	AA		30.46
16	0553	12	CLR	10.00		32	0.0	29	-1.7	23	-5.0	69	8	010		30.44	1	002	30.46	AA		30.46
16	0653	12	CLR	10.00		32	0.0	29	-1.7	23	-5.0	69	9	010		30.44			30.46	AA		30.46
16	0753	12	CLR	10.00		34	1.1	30	-1.0	23	-5.0	64	10	010		30.45			30.47	AA		30.47
16	0853	12	CLR	10.00		37	2.8	31	-0.3	21	-6.1	52	11	020		30.45	0	005	30.47	AA		30.47
16	0953	12	CLR	10.00		40	4.4	33	0.6	21	-6.1	47	11	050		30.44			30.46	AA		30.46
16	1053	12	CLR	10.00		43	6.1	35	1.6	21	-6.1	42	8	030		30.42			30.44	AA		30.44
16	1153	12	CLR	10.00		43	6.1	36	2.2	25	-3.9	49	7	120		30.38	8	024	30.40	AA		30.40
16	1253	12	CLR	10.00		45	7.2	37	2.8	25	-3.9	46	6	VR		30.33			30.36	AA		30.35
16	1353	12	CLR	10.00		48	8.9	39	3.9	26	-3.3	42	9	130		30.27			30.29	AA		30.29
16	1453	12	CLR	10.00		49	9.4	40	4.4	27	-2.8	43	13	140		30.23	6	051	30.25	AA		30.25
16	1553	12	M	10.00		49	9.4	41	4.9	30	-1.1	48	9	150		30.22			30.24	AA		30.24
16	1653	12	CLR	10.00		48	8.9	41	5.0	32	0.0	54	9	130		30.19			30.22	AA		30.21
16	1753	12	CLR	10.00		47	8.3	41	4.9	33	0.6	58	8	150		30.17	8	021	30.19	AA		30.19
16	1853	12	CLR	10.00		45	7.2	41	4.8	35	1.7	68	7	160		30.15			30.18	AA		30.17
16	1953	12	CLR	10.00		46	7.8	42	5.5	37	2.8	71	6	150		30.14			30.16	AA		30.16
16	2053	12	CLR	10.00		47	8.3	43	6.3	39	3.9	74	6	170		30.15	5	007	30.17	AA		30.17
16	2153	12	CLR	10.00		49	9.4	45	7.3	41	5.0	74	6	170		30.15			30.17	AA		30.17
16	2253	12	CLR	10.00		48	8.9	45	7.3	42	5.6	80	5	180		30.13			30.15	AA		30.15
16	2353	12	CLR	10.00		50	10.0	47	8.1	43	6.1	77	7	VR		30.11	8	014	30.13	AA		30.13

Table 2. Local weather conditions on the day of the imagery collection.

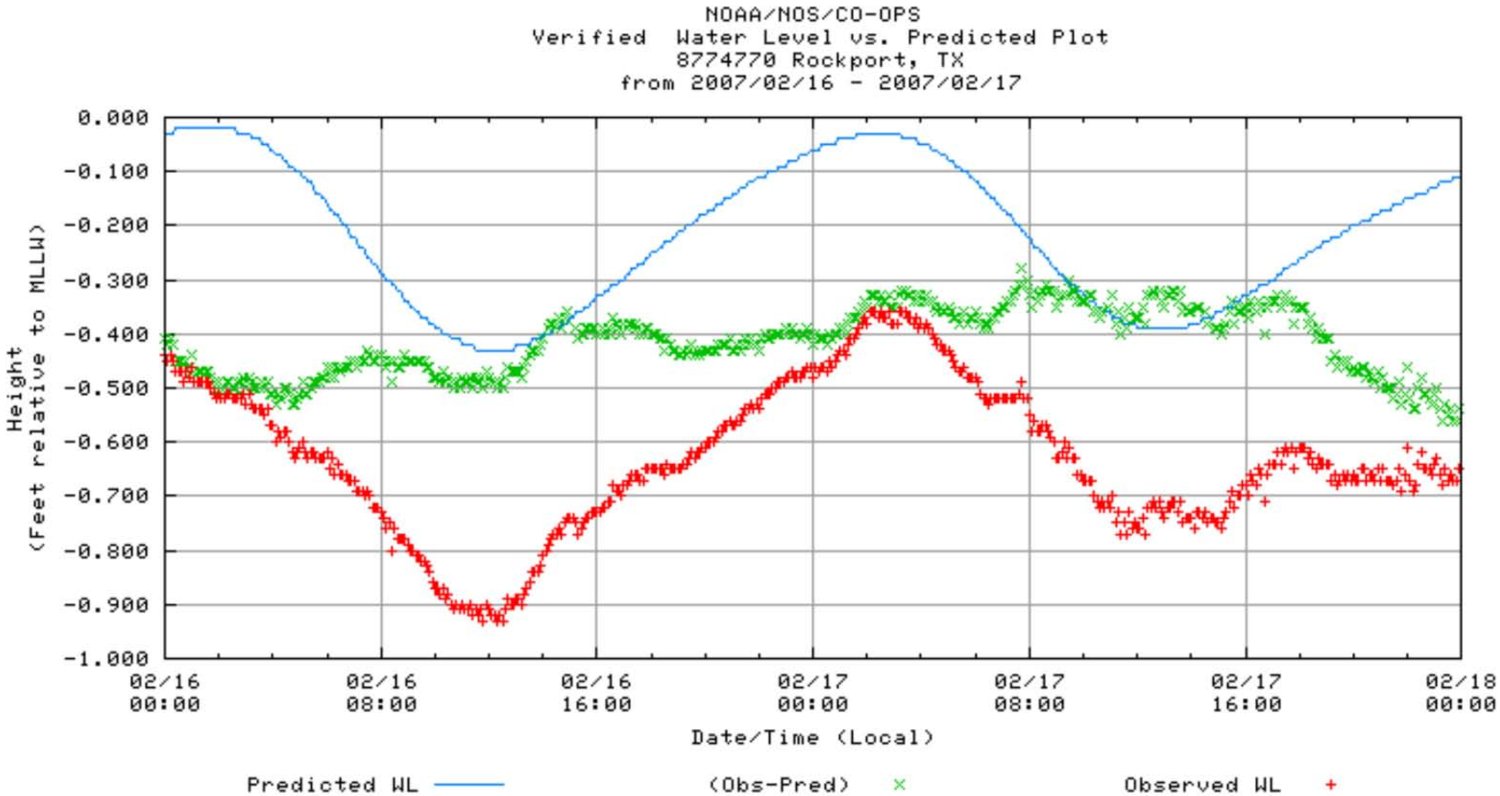

Figure 4. Tides at the Rockport Station on Feb. 16 and 17, 2007

Table 3. Environmental conditions and image characteristics

	Contract Specifications	***UltraCam***	***DMC***	***ADS40-52***
Environmental Conditions				
Operator		Sanborn Map Company	PhotoScience	Fugro-Earthdata
Altitude (in feet)	none	9300	8200	7920
Date of Collect	Fall, 2006	2/16/2007	2/16/2007	2/16/2007
Time of Collect (Central Time)	Implied in sun angle specifications	11:03am to 12:58pm	1:03pm to 1:42pm	1:58pm to 3:06pm
Sun Angle of Collect	30□0n Angle of Collect specifi	42□2n Ang	50□0n Ang	38□8n Ang
Approximate Tidal Range (in feet)	none	-0.90 to -0.93 to -0.89	-0.89 to -0.84	-0.83 to 0.74
Approximate Range in Wind Speed	none	6-8 mph	6-9 mph	9-13 mph
Image Characteristics				
Radiometric Resolution	8-bit	8-bit	16-bit	8-bit
Tiling	DOQQ with 100m buffer	DOQQQ with 100 - 150m buffer	DOQQwith 100 - 200m buffer	DOQQQ with 100 - 200m buffer
Spatial Resolution (in meters)	0.25m	0.25m	0.25m	0.25m
Spatial Accuracy Calculated from NOAA Independent Control Points (NSSDA) (in meters)	+/- 5.0 at CE 95%	+/- 1.339	+/- 0.684	+/- 0.742 *
Spatial Accuracy Reported by Operator (in meters)	+/- 5.0 at CE 95%	0.94 (4 samples)	0.43 (10 samples)	0.27 (6 samples)
Projection and Datum	UTM 14/NAD83	UTM 14/NAD83	UTM 14/NAD83	UTM 14/NAD83/86
Spatial Offset Between Bands	No more than 1 pixel	None apparent	None apparent	None apparent
Format	Uncompressed TIFF	Uncompressed TIFF	Uncompressed TIFF	Uncompressed TIFF
Pyramid Layer	Yes	None	None	None
Existence of Bad Pixels	None	None	None	Zero pixels in shadows of RGB image
Spectral Resolution	Best possible	Single image with B, G, R, NIR	CIR and RGB composites	CIR & RGB composites; single image with B, G, R, NIR

** Less than 20 minimum ICPs available for ADS40-52 assessment*

Table 4. Reprocessing steps required for each image data set

System	Tile	Radiometric Resolution	No. Bands/Spectral Resolution	Spatial Resolution	Processing Steps Required
ADS40-52	Quarter Quad	8	3 (B, G, R,/G, R, NIR)**	0.25m	Create 4-band images
UltraCam	Quarter-Quarter Quad	8	4 (B, G, R, NIR)	0.25m	Merge to Quarter Quad
DMC	Small Rectangle	16	4 (B, G, R, NIR)	0.25m	Rescale to 8-bit

*** Fugro Delivered 2 images per quarter quad; 1 RGB and 1 CIR composite*

Figure 5. Example of ADS40-52 data over a small portion of Redfish Bay.

Figure 6. Example of DMC data over a small portion of Redfish Bay.

Figure7. Example of UltraCam data over a small portion of Redfish Bay.

A. Quantitative Review

1. Spatial Accuracy

Each operator was required to provide NOAA with spatial accuracy statistics developed from independently surveyed sample points. Table 3 shows the accuracies reported by each operator. However, none of the operators collected enough samples to satisfy the National Standard for Spatial Data Accuracy (NSSDA) standard of at least 20 points; with Photo Science collecting 10 points, Fugro EarthData collecting 6 points and Sanborn collecting 4 points.

To independently evaluate the spatial accuracy of the three Redfish Bay data sets, NOAA personnel measured GPS coordinates at 23 photo-identifiable features in the study area. The points were selected according to the following criteria:

- The point was a fixed feature clearly distinguishable in all image sets.
- A clear GPS signal could be received at the point (i.e. no overhanging structures, etc.).
- The points were well distributed throughout the imagery.
- The points had clear-short baseline distances to reference stations for differential correction.

Each point was measured for 5 minutes at a 1 second interval (300 records) using a Thales Z-Max survey-grade GPS receiver. The points were then differentially corrected using the Aransas Pass CORS station operated by U.S. Coast Guard (ARP5) and Thales GNSS Solutions software. The longest baseline between the reference station and any of the Independent Control Points (ICPs) was 13.3 km. The differential correction resulted in an average horizontal accuracy of the surveyed points of 2.9 cm. A set of corresponding image points were then obtained from each of the three images by visually locating the survey feature in the image and creating a point shapefile. The image point coordinates were compared to the field surveyed points according to the FGDC NSDDA methodology. This test was applied using the circular error protocol at the 95% confidence level (CE 95). The results showed all image sets had very comparable spatial accuracy that greatly exceed the contract standard of ± 5 meters and most of the spatial accuracy requirements for landscape scale benthic habitat mapping. Table 3 displays the NSSDA statistics from the NOAA surveyed samples for each image data set. Of the three sensors, the DMC had the best NSSDA accuracy (± 0.684m) followed by the

ADS40-52 (± 0.742m) which is followed by the UltraCam. (± 1.339m). It should be noted that only 19 independent control points fell within the ADS40-52 coverage. This is below the minimum of 20 points for a statistically valid NSSDA test. Additional ICPs would improve the accuracy of the ADS40-52 result.

A one-way Analysis of Variance (ANOVA) was performed to test of statistical significance of the differences between each sensor's estimated root mean square error (RMSE). The results show that the UltraCam RMSE is significantly different from the DMC and ADS40-52 at the 95% confidence level. However, the ADS40 and DMC RMSEs are not significantly different from one another at the 95% confidence level.

2. Histograms

Figures 8-11 display the histograms of each of the four bands from each image data set. In the visible bands (1-3), the histograms have similar distributions and shapes, but the UltraCam histograms appear to be normally distributed and are consistently narrower than those of the DMC or ADS40-52 imagery, indicating that the UltraCam imagery has a narrower and probably less sensitive spectral range than the ADS40-52 or the DMC. Additionally, the UltraCam band 4 histogram peaks at a much higher DN value than what would normally be expected for a near infra red sensor. Discussions with Microsoft concerning the UltraCam histograms indicate that the shapes of the histograms are a function of mosaic processing performed by the operator - the Sanborn Map Company. Because mosaics were a deliverable to NOAA, each of the operators performed mosaic processing on their imagery.

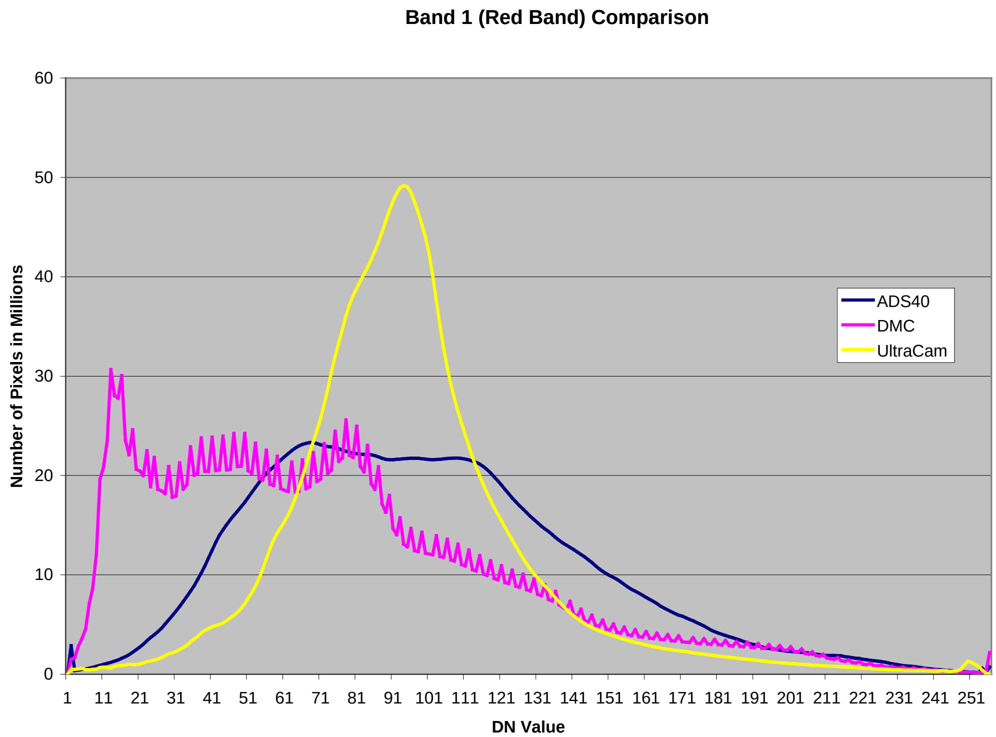

Figure 8. Histograms band 1 for all three data sets.[5]

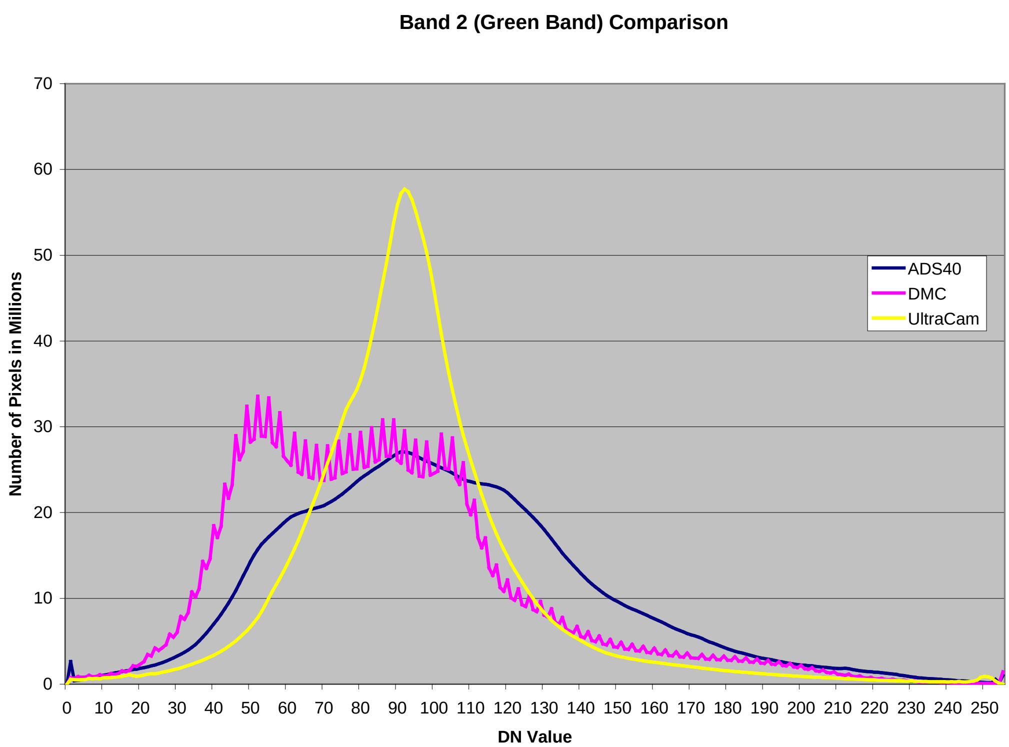

Figure 9. Histograms band 2 for all three data sets

[5] The DMC imagery was delivered as a 16 bit data file. However, the data was actually collected in 12-bit radiometric resolution. The delivered 16-bit data is actually 12 bits of data distributed across a 16 bit radiometry. The delivered DMC data was rescaled in ERDAS Imagine to create images with 8-bit radiometric resolution. During this process, a large number (approximately 260) of the 16 bit DNs were remapped to a single 8-bit DN. Generally, somewhere between 6 and 8 of the approximately 260 DNs are non-zero and it is this variation that causes the spikiness in the rescaled histogram. If there are only 6 non-zero DNs, then the corresponding DN in the rescaled image's histogram will be a trough; if there are 8 non-zero DNs, then the corresponding DN in the rescaled image's histogram will be a spike.

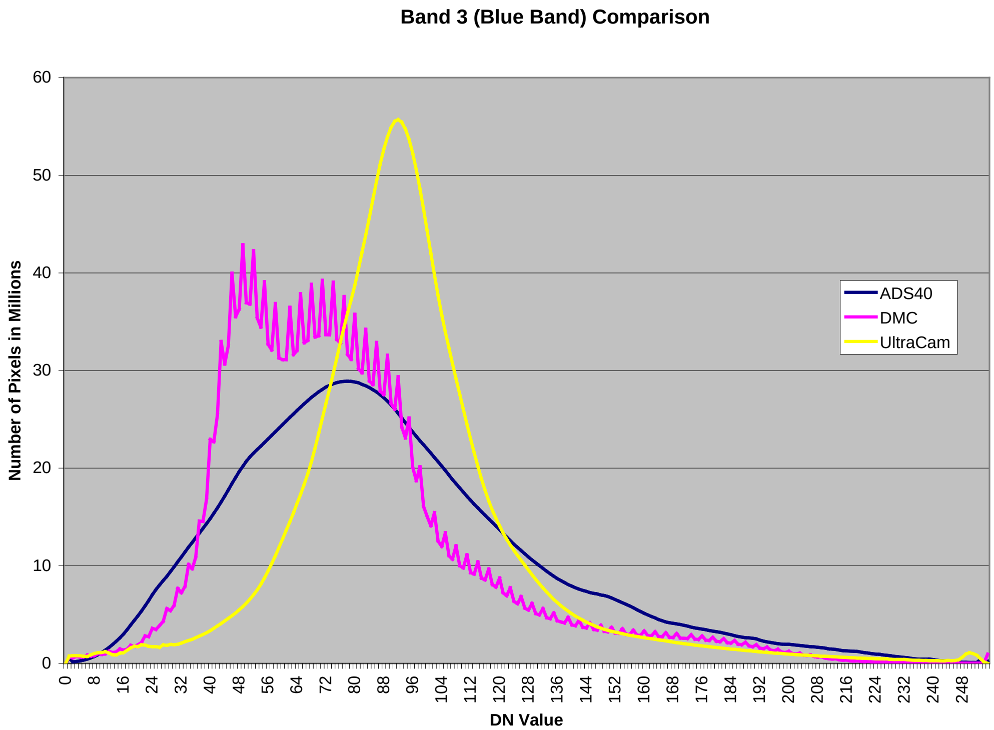

Figure 10. Histograms band 3 for all three data sets

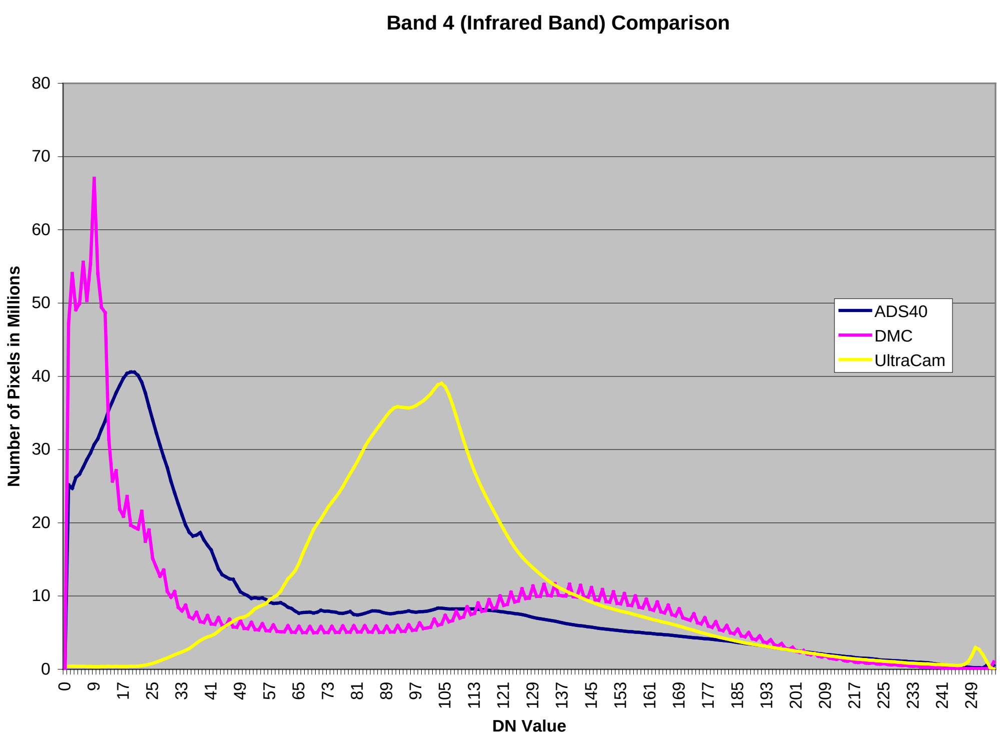

Figure 11. Histograms band 4 for all three data sets

3. Edge Detection

During the flights John Wood of the Harte Research Institute for Gulf of Mexico Studies submerged three 2-meter by 2-meter targets (see Figure 12) at 1, 1.5, and 2 meters depth in the study area. Figure 13 shows the distribution of the targets in the project area and Figures 14-16 compare natural color images of each target in each of the three image data sets.

Figure 12. One of the targets prior to submergence

The targets are visible and the target pattern is evident in each image set. Additionally, the images of the targets appear to be almost indistinguishable from one another at each depth. Unfortunately, comparative relative edge response analysis (Blondski, et al, 2004) of the image targets was not possible because not enough pixels per target were available for sampling.

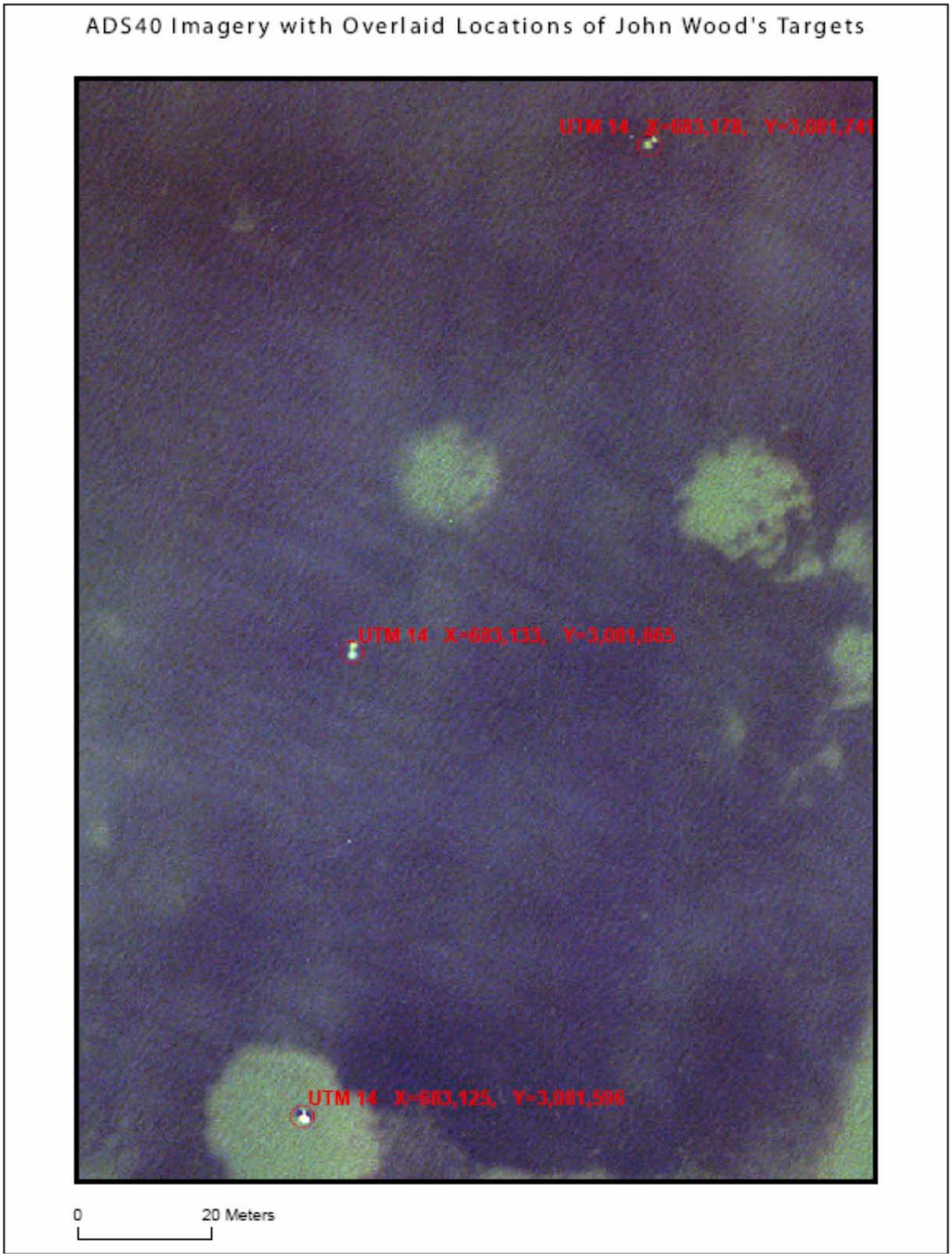

Figure 13. Distribution of the submerged targets. From north to south, the depths of the disks are 1 meter, 1.5 meters, and 2 meters.

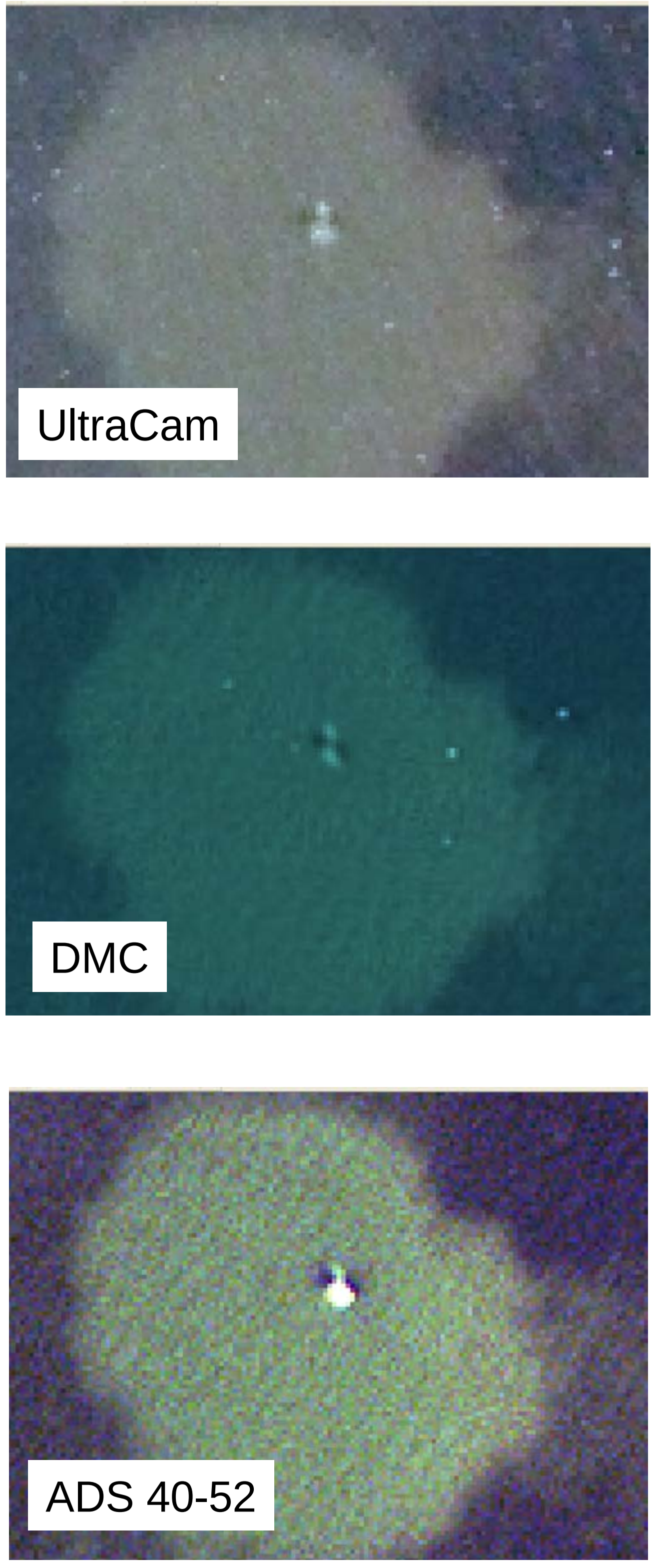

Figure 14. Comparison of submerged targets at 2 meters depth

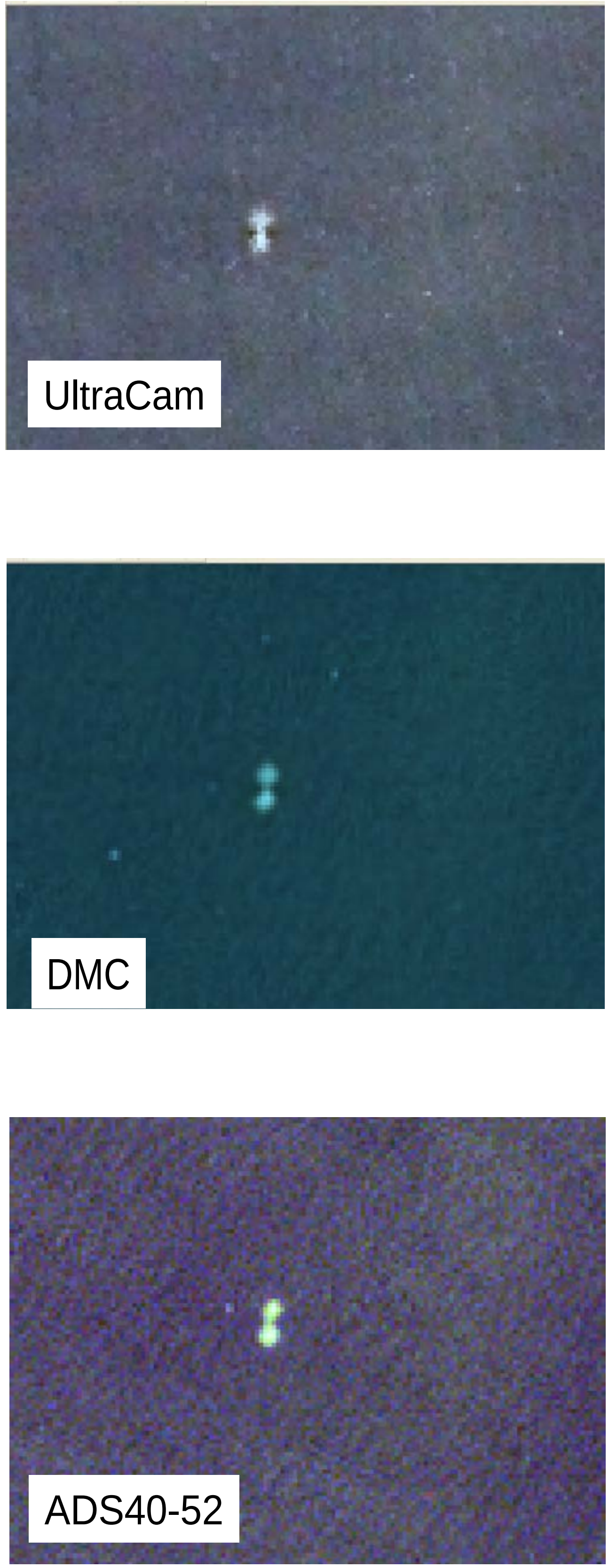

Figure 15. Comparison of submerged targets at 1.5 meters depth.

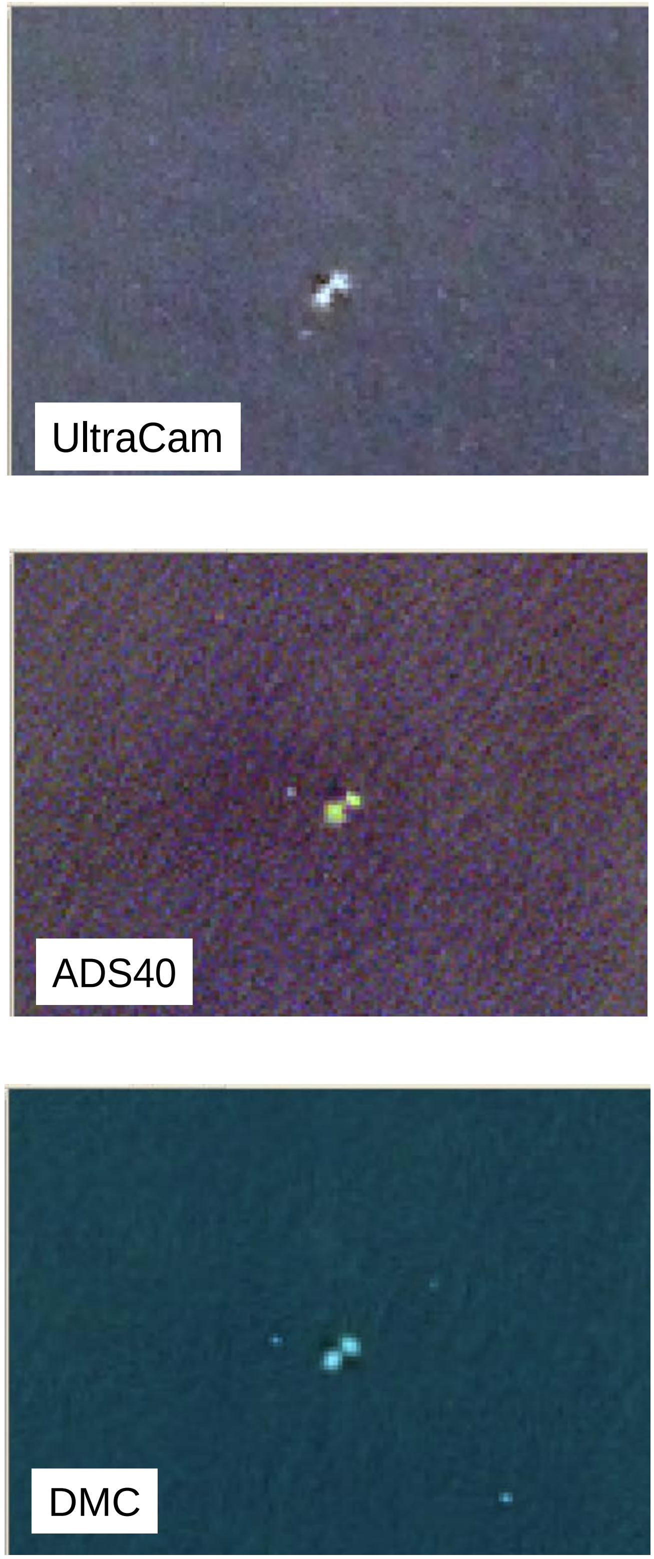

Figure 16. Comparison of submerged targets at 1 meters depth.

4. Bi-Spectral Plots of Benthic Habitat Class and Propeller Scars

The final quantitative review of the image sets involved the creation of comparative bi-spectral plots of elipses representing multiple samples of propeller scars or benthic habitat class from the project area. Each ellipse represents the bi-spectral space of each sample's DN mean plus or minus one standard deviation. Overlap between elipses of different classes indicates that the classes are spectrally confused at one standard deviation. In 2006, Fugro Earthdata mapped the benthic habitat of Redfish Bay using NAIP imagery. One of the products of the pilot project for the benthic mapping project was the intense sampling of benthic habitat classes in Redfish Bay. Multiple samples of each benthic class were delineated and labeled using either field validation or manual image interpretation.

To compare the spectral response by habitat class of each band of each image set, bi-spectral plots were created for each possible combination of bands (i.e. band 1 vs. band 2, band 1 vs. band 3, band 1 vs. band 4, band 2 vs. band 3, band 2 vs. band 4, and band 3 vs. band 4) across benthic habitat types. For all sets of imagery, the greatest spectral distance between benthic habitat classes occurs in the visible versus the near infrared bands. Figures 17-19 compare propeller scar samples to continuous sub-aquatic vegetation (SAV) samples. Figures 17 and 18 show that propeller scars are most distinct from SAV in the DMC data, with the ADS40-52 data showing the next best separation, and the UltraCam data showing the most confusion.

As Figure 19 shows, very little spectral distance exists between propeller scars and sub-aquatic vegetation in the visual bands. Because visible bands are highly correlated, all other comparisons of the visible bands showed similar confusion across all three image data sets.

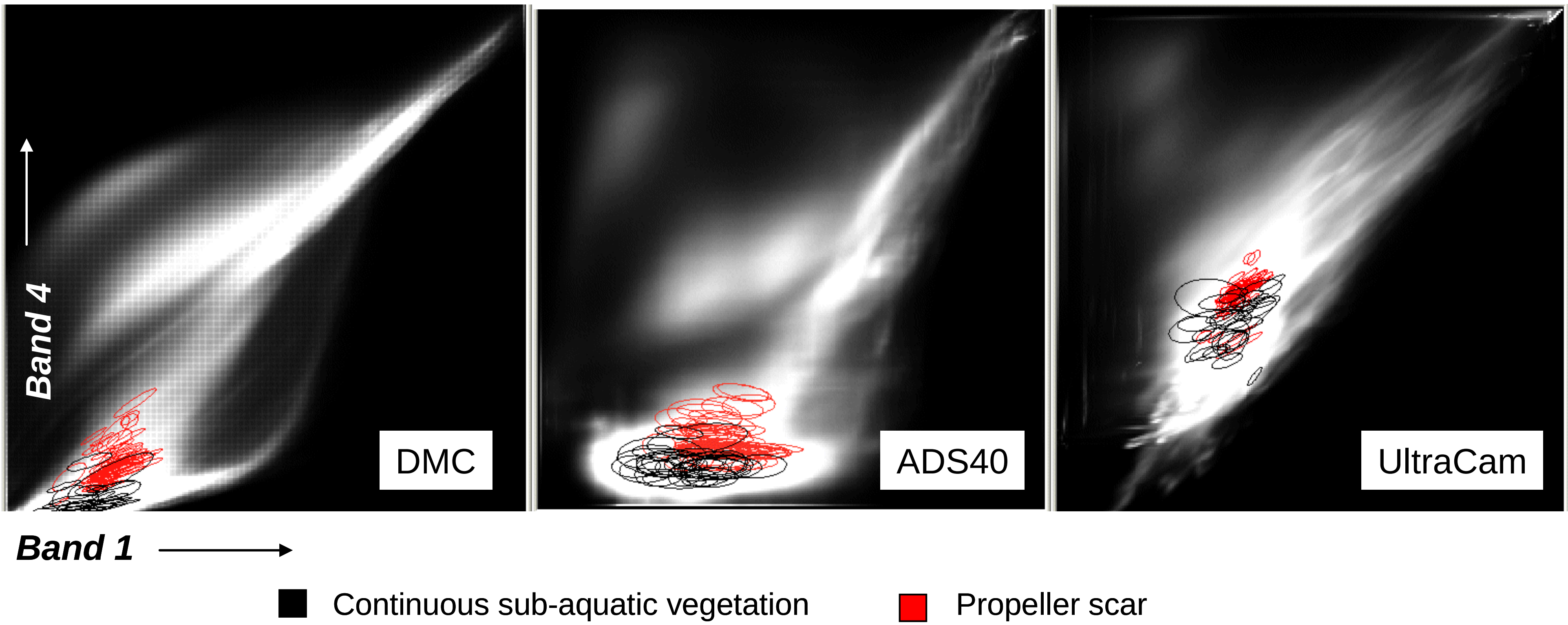

Figure 17. Bi-spectral plot showing propeller scar and continuous sub-aquatic vegetation in band 1 vs. band 4.

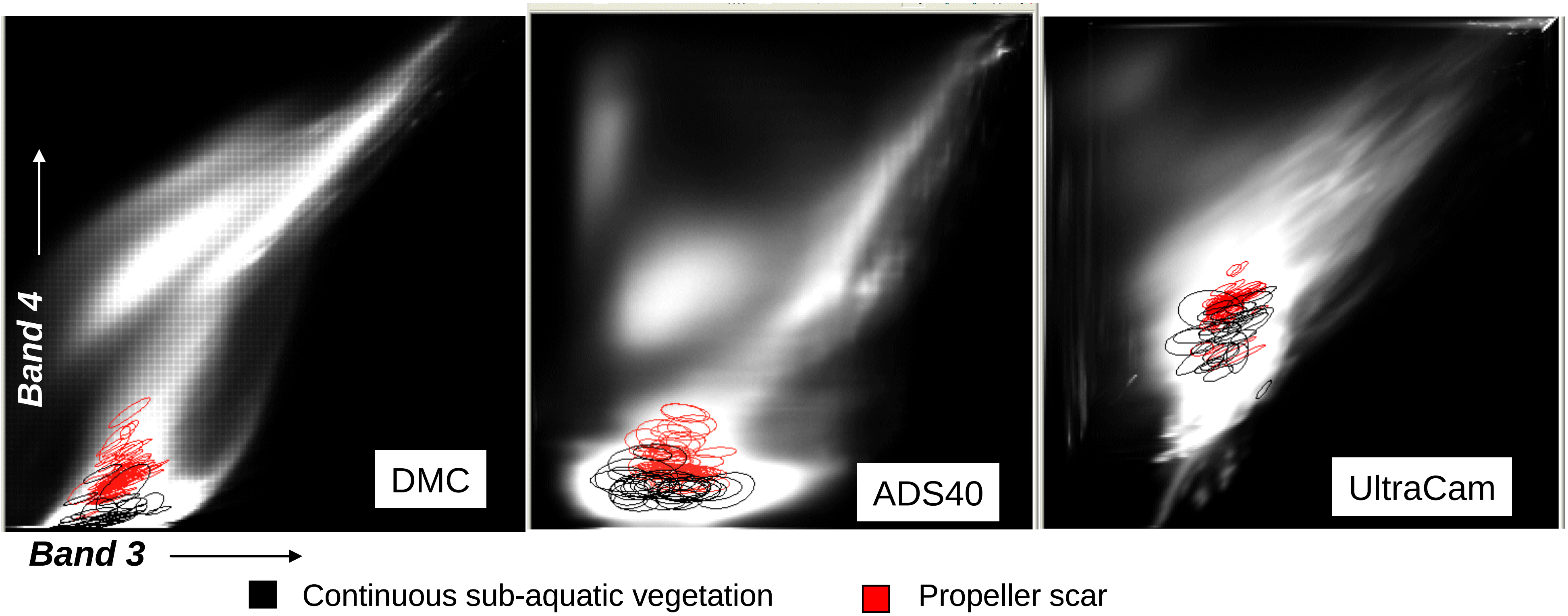

Figure 18. Bi-spectral plot showing propeller scar and continuous sub-aquatic vegetation in band 4 vs. band 3.

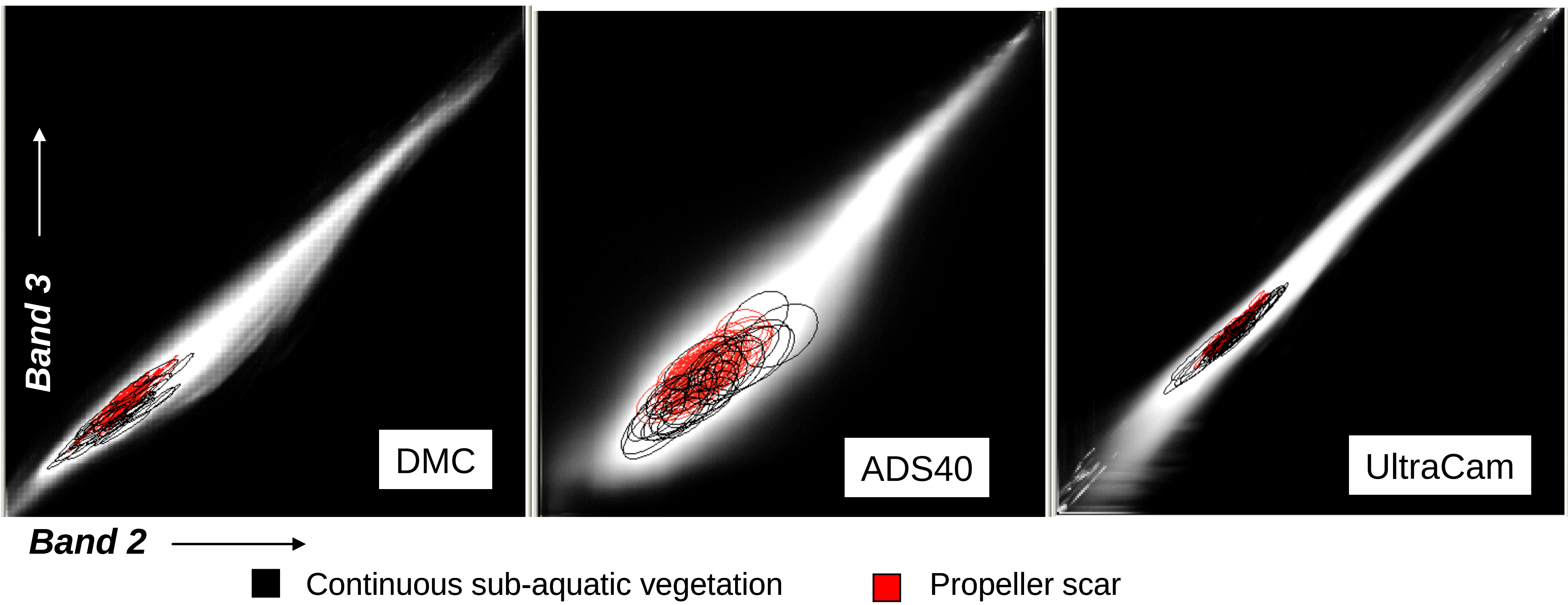

Figure 19. Bi-spectral plot showing propeller scar and continuous sub-aquatic vegetation in band 2 vs. band 3.

Comparing other benthic classes (e.g. continuous sub-aquatic vegetation, mangroves, bivalve reefs, and unconsolidated sediments) to one another and to propeller scars, as shown in Figures 20 and 21, shows that mangroves are spectrally unique in all image sets. However, bi-valve reefs and unconsolidated sediments show some confusion between each other and with propeller scars and SAV. They are most distinct in the DMC data, closely followed by the ADS40-52 data, with the UltraCam again showing the most confusion. Bivalve reefs and unconsolidated sediments can be difficult to distinguish based solely on their spectral response. Bare shell can mimic unconsolidated sand or gravel. Additionally, oyster shells often support a thin diatom veneer that produces an infrared response which can also result in confusion with macroalgae or sparse seagrass. Unconsolidated sediments can have a wide variety of tones and textures that may make them indistinguishable from surrounding habitats, especially as depth and turbidity increase. Successfully breaking out bivalve reefs and unconsolidated sediments from the other classes with any of the image data sets may require field visits or additional data (such as shape or texture), or manual editing.

An interesting finding of the bi-spectral comparison is the importance of the infrared band in distinguishing benthic habitat classes and propeller scars in shallow water. Because the infrared band does not penetrate water as deeply as the visible bands, it has long been assumed to be less effective than the visible bands in the classification of submerged aquatic beds (Philipson, 1997). However, this analysis and other work (Green and Lopez, 2007) indicate that, in water less than 3 meters in depth, the infra red band can be an important distinguisher of benthic habitat classes.

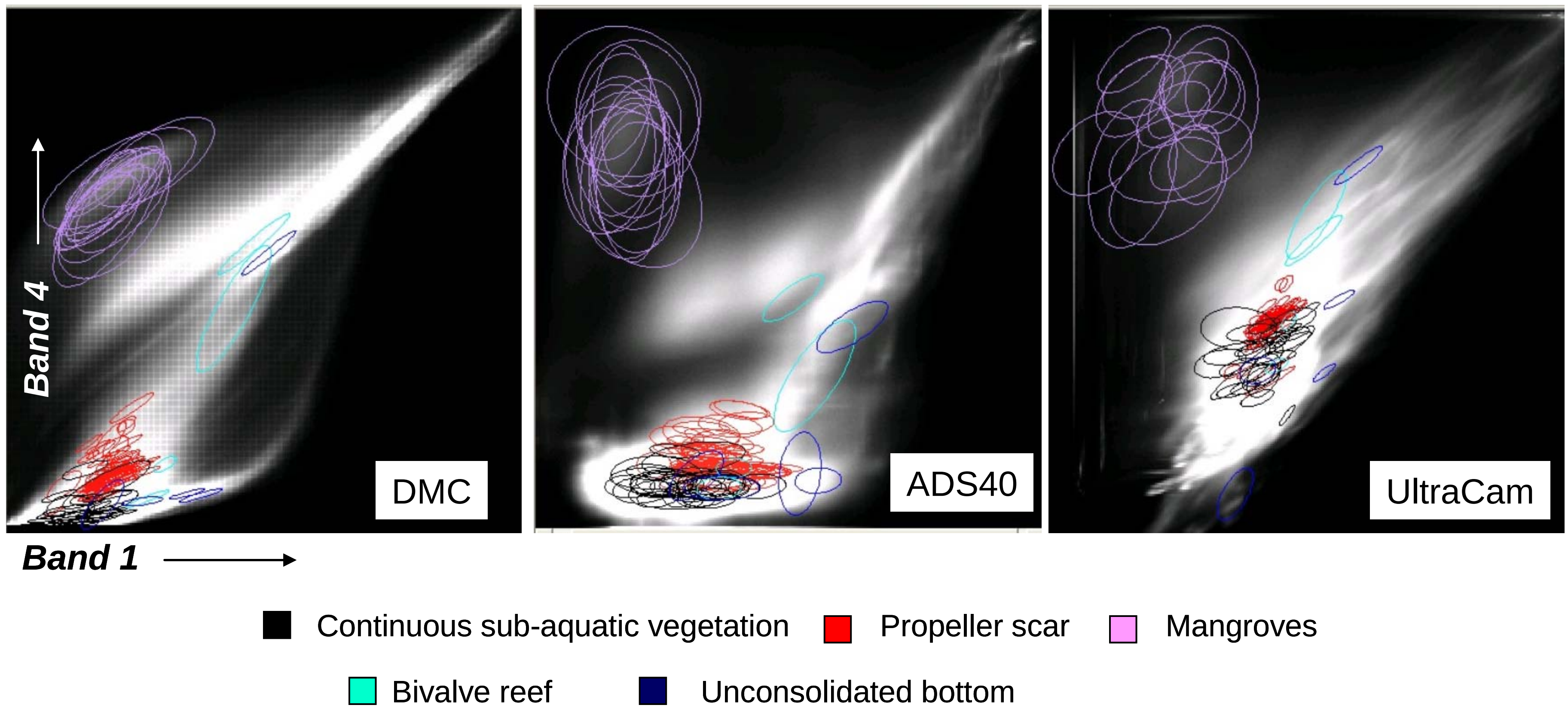

Figure 20. Bi-spectral plot showing propeller scar and all benthic habitat classes in band 1 vs. band 4

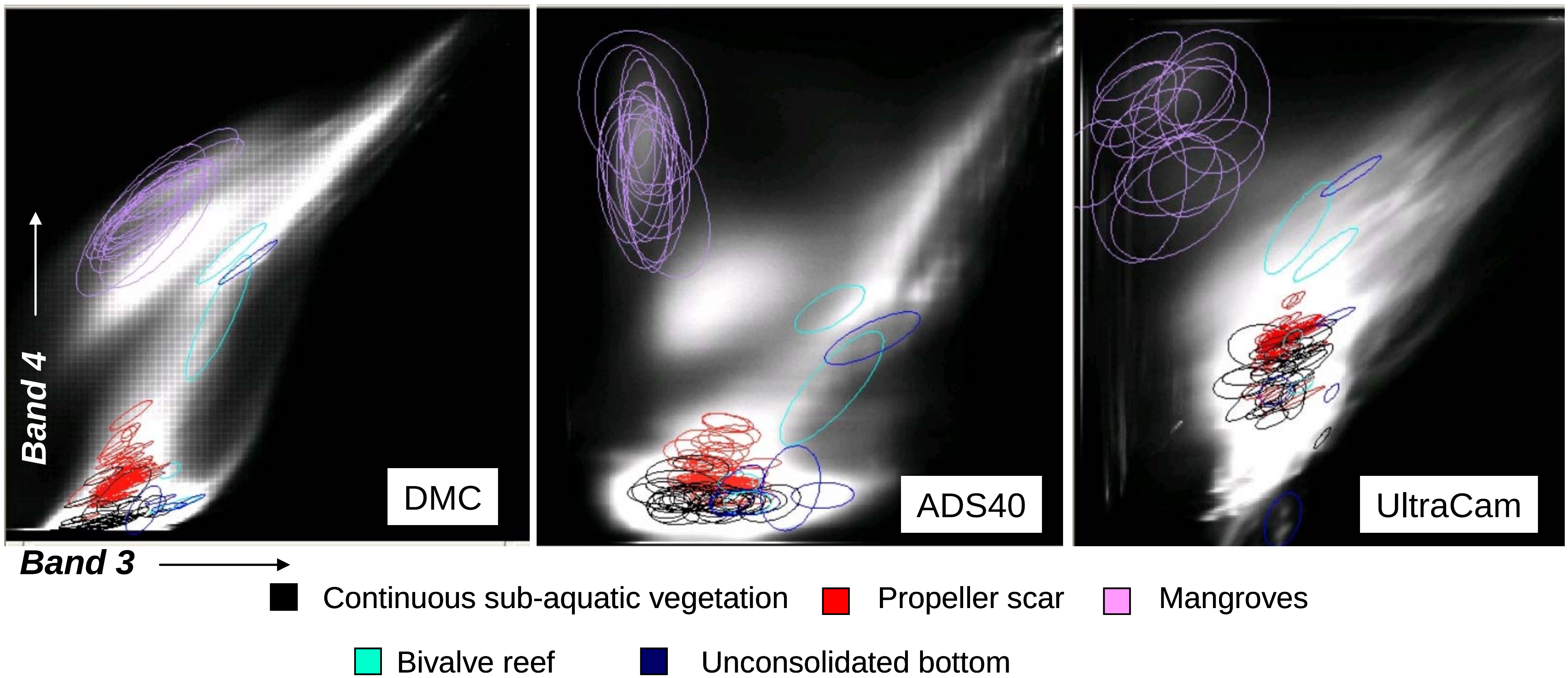

Figure 21. Bi-spectral plot showing propeller scar and all benthic habitat classes in band 3 vs. band 4.

B. Qualitative Review

All of the image sets were also reviewed by five remote sensing professionals, three of whom were also benthic habitat mapping experts. The purpose of this qualitative evaluation was to determine the suitability of the imagery derived from the three sensors to map benthic habitat. Benthic habitat classes to be considered were Continuous and Patchy Submerged Rooted Vegetation, Unconsolidated Sediments, Bivalve Reef, Unknown Benthic Habitat, Mangroves, Emergent Marsh, and Other Land. The image footprints reviewed by the experts corresponded with the 7.5 minute U.S.G.S. quarter quad boundaries. The reviewers were asked to perform their evaluations on computer workstations using software that allowed side-by-side comparisons between all three data sets. Software utilized included ArcGIS and ERDAS Imagine. The benthic habitat reviewers were also requested to fill out a template that ranked the imagery data sets for mapping each of the benthic classes.

The overall assessment of each of the reviewers was that the imagery was entirely adequate for mapping purposes in general and for benthic mapping specifically. Quotes of general praise from the reviewers included:

> "The imagery for all of the data sets was tone corrected for good contrast in the shallow water areas."
>
> "Overall, the prop scars are clearly visible in all 3 sets of imagery…"
>
> "The three systems appear comparable in the ability to clearly render SAV and other types of shallow water features."
>
> "The imagery from all three systems clearly shows propeller scarring, even very fine and detailed networks of scarring are clearly visible in the imagery from all three systems."

While the reviewers stated that all image data sets were sufficient, they also found general problems:

> "Overall, each sensor had pros and cons associated with each comparative classification. The ADS40, DMC and Ultra Cam all

have weak areas associated with accurate color rendition depending on the cover type signature being viewed"

"There are many instances of isolated bright pixels in the imagery of all 3 cameras that cannot be positively attributed to surface reflection."

"…every instrument exhibited some artifacts that could be improved with superior calibration and processing techniques."

However, the reviewers came to no consensus as to the relative rank of the data sets. Conflicting comments included:

"The consistency of color was best in the data collected by the Vexcel system."

"The Vexcel rendition was low in contrast in areas of open water."

"[the Vexcel system] Seems to have the most clarity issues."

"[the DMC has the] Best overall color balance."

"The DMC sensor produced better results then the other sensors for submerged features."

"There are dramatic mosaic lines in some photoscience images, especially over water where specular reflections changed between the collections"

"The ADS40 had the overall lowest average score of the three for submerged features, but scored above average for Mangroves."

"Of the 3 sets of imagery, the ADS40 appears to be the most uniform in color/tone across the region"

"The ADS40/SH52 infrared rendition showed excellent contrast in water areas while maintaining detail in the upland vegetation and was judged the best overall infrared rendition."

IV. Review of the Methods Use to Create the Propeller Scar Maps

While prop scar mapping is much less complex than benthic mapping, it still requires the same approach of understanding how and why benthic habitat characteristics vary in the field; and capturing and classifying all the variation in the imagery and ancillary data sets that is related to the variation in the classification scheme. Steps implemented to create the prop scars maps from each imagery set included

A. Creation of processing regions
B. Calibration trip
C. Sample site collection
D. Validation trip
E. Use of Feature Analyst to map prop scars
F. Modeling
G. Accuracy Assessment

The main purpose of the automated prop scar mapping was to compare the effectiveness of the three image datasets for automated mapping of prop scars. To ensure that the comparison was unbiased, the preparation steps, input data, training site delineations, and Feature Analyst classification workflow used on each image dataset were identical. Absolutely **no manual editing** was conducted on the finished map products.

A. Creation of Processing Regions

Because the image data sets were so large, the project area had to be grouped into 5 processing regions (see Figure 22) for automated image classification. The processing regions also represent contiguous areas of *relatively* similar benthic conditions. For this reason, the processing regions were a better alternative then arbitrary quarter quads boundaries. The figure below shows the processing regions used to make the prop scar maps, as well as the U.S.G.S. quarter quad boundaries.

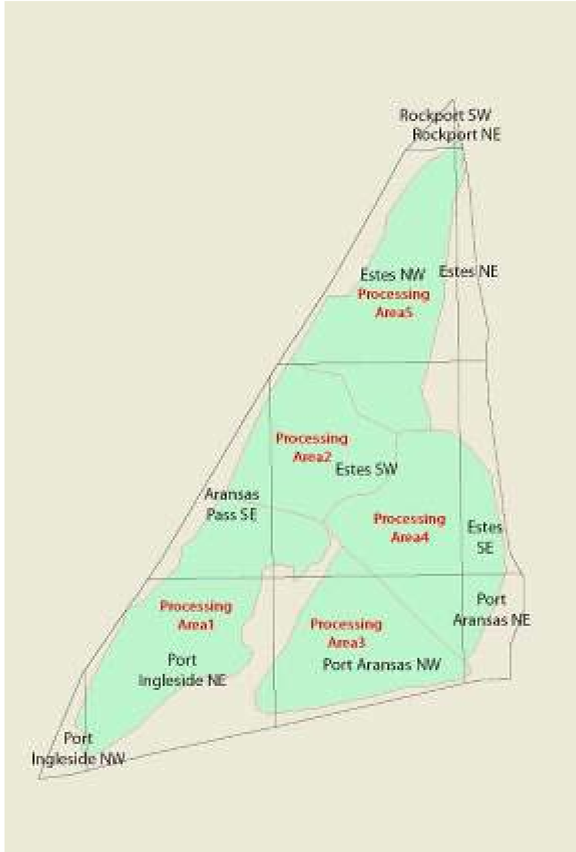

Figure 22. Processing regions for automated prop scar mapping.

B. Calibration Trip

The primary purpose of a calibration trip is to learn what causes variation in occurrence among the classes to be mapped. Having the imagery, digital field forms, and ancillary data on laptops linked to GPS greatly increases the effectiveness of the calibration trip because field personnel can be certain of their location, and benefit from both a ground and bird's eye view.

Between October 18th and October 20th, 2006th the project team met in Texas for the project kick off meeting and a prop scar calibration trip. The trip was conducted by boat and provided the mapping team with the opportunity to see the range of prop scars in the Bay. Dennis Pridgen, who is an expert in the ecology and management of the Bay, led the trip. A GPS enabled laptop running ArcMap GIS software was used to help navigate. As actual prop scars were visited by boat, analysts were able to see the same scars on 1-

meter resolution NAIP imagery[6] displayed on the laptop screen. By doing so, the analysts were able to "calibrate" their eyes to what a prop scar actually looked like on the imagery. Calibration was done for the full range of prop scars: those that were light in tone, those that were dark in tone, thin scars, thick scars, etc.

C. Sample Site Collection

Sites to be used for both Feature Analyst Classifications or for accuracy assessment, were collected from three sources: transects swum by Texas Parks and Wildlife, field work conducted by boat, and polygons "heads up" digitized by the image analyst. All of the sites are stored in a single feature class. The three types of sites are described in more detail below.

Sites Collected from Transects Swum by Texas Parks and Wildlife Department. The Texas Parks and Wildlife Department has been swimming fixed 100 meter transects and collecting the GPS location of every prop scar that the transect swimmer crosses. GPS Data from the 2006 and 2007 transects were acquired by the mapping team and overlaid on the three image datasets. Where a prop scar was apparent on all three image data sets at the location of the GPS'd point, a polygon of the prop scar was digitized and became a sample site.

The swimmers collected most of their GPS transect points in the summer of 2006. The three image datasets were collected in February, 2007. Approximately one third of the scars that were visible to the swimmers were not visible on the imagery in the same location.

Sites Collected by Boat. The image analyst spent two days working on Redfish Bay in September, 2007. During this trip, new training sites were collected. The new sites were first identified visually on the project imagery. Then, using a GPS enabled laptop running ArcMap GIS software for navigation, the site was visited in the field. At each site GPS coordinates, water depth, and scar width were recorded. All sites visited by boat were attributed as "field validated" for the purposes of accuracy assessment and general reference.

[6] At the time of the calibration trip, the three imagery data sets had not yet been collected.

Sites Collected by "Heads Up" Digitizing. The majority of sites used for accuracy assessment and for Feature Analyst classifications were digitized from the three sets of imagery. Heads up digitizing consisted of a GIS analyst visually identifying a prop scar on the three sets of project imagery, digitizing a polygon around the perimeter of the prop scar in ArcGIS, and adding the polygon as a site.

During the field validation trip, approximately 50 of the "heads up" digitized sites were field validated. Approximately 7-10 "heads up" digitized sites could not be validated because in the time between image collection (2/2007) and field validation (9/2007) as they had been filled in by fast growing annual sea grasses.

D. Validation Trip

The validation trip occurred in September, 2007. The purpose of the trip was to validate as many "heads up" digitized sites as possible and to collect a additional boat-collected sites. The project team waited for a window where low winds, low tides, and water clarity made it possible to actually see the bottom in the areas of prop scarring.

The image analyst and Texas Parks and Wildlife Department personnel, guided by a GPS enabled laptop running ArcMap GIS, identified scar sites that had been "heads up digitized" off of the three sets of imagery. Using the laptop, the project team could navigate to the precise location of the scar site in question. When a site was reached the team first validated the existence of the prop scar. If the scar was present, water depth and scar width were measured and recorded in the site's feature class. Analysts also took note of the characteristics of the scar (i.e. light or dark in tone, occupied by wrack or sea grass, etc.).

A number of the "heads up" digitized sites were not visible from the boat during field work. The vast majority of those not visible were completely filled in with widgeon grass. Widgeon grass is a fast growing, annual seagrass that had filled in a number of the scars between the date of image collection (February, 2007) and the date of the field trip (September, 2007).

Following collection of the sample sites, a random number generator was used to randomly select a subset of 50 prop scar and non prop scar sites for accuracy assessment. These sites were put aside and were not used during image classification.

E. Use of Feature Analyst to Create the Propeller Scar Maps

Feature Analyst is a machine learning algorithm that takes training sites as input and extracts features of similar appearance from the imagery. It was initially developed for DOD applications, and is useful in automatically extracting features such as roads and buildings from multispectral digital imagery.

The inputs to the software are the imagery itself, training sites of the features to be extracted, and a number of parameters for the classifier including the input representation which give the classifier the ability to consider spatial context. Considerable time was spent at the outset of the project exploring the most effective combination of training sites and parameters for using Feature Analyst to map prop scars. After testing a myriad of combinations of the following parameters on a small subset of the project area, the following parameters were selected as optimal for prop scar mapping.

Input Bands: All (NIR And R,G,B)
Find rotated instances of features: Turn on
Learning algorithm: General purpose
Aggregate Areas: 4 pixels (later aggregated up to MMU using eliminates)
Resample Factor: 1 (image data is not resampled)
Apply Histogram Stretch: No

Several tests were also run to evaluate the efficacy of segregating dark-toned scars from light-toned ones or separating narrow and wide scars into separate classifications. However, the tests clearly indicated that these measures were ineffective and that the most effective propeller scar map produced by Feature Analyst resulted from a single classification using a small number of light-toned, average width, propeller scar training sites.

The processing regions represent contiguous areas of *relatively* similar benthic conditions. Training sites were selected for each processing region. Sites that had been set aside for accuracy assessment were not available in the pool of sites used for training. Analysts made sure that selected training site scars were equally apparent on each set of imagery. Analysts were also careful that training sites were perfectly registered to **each** set of imagery before any classifications were run. Feature Analyst classifications were run on each processing region in each image data set. There were 15 Feature Analyst classifications run in all. After classifications were complete, analysts did several things to refine the raw classification outputs. These steps included:

- Combining the mapped scars for the 5 processing regions into one layer for each image data set
- “Masking out” mapped prop scars for areas that were **not** mapped as patchy SRV, continuous SRV, bivalve reef, and unconsolidated sediments in the benthic map developed by Earthdata
- Performing a single pass of "remove clutter by shape" on all the combined scars for each image data set. “Remove clutter by shape” is a tool in Feature Analyst that automatically removes errors of commission after a classification is run. In this case, the tool was used to remove mapped features that were not linearly shaped. There are a number of parameters for the tool. In this case the “invariants” metric was employed.

F. Additional Modeling

After the three prop scar maps were completed for each of the three image datasets, quantitative accuracy assessment and qualitative map review demonstrated that the prop scar map made from the ADS40-52 data was significantly more accurate than the maps created from the other data sets. To increase the utility of the prop scar map for management purposes by the State of Texas, the map produced from the ADS40-52 data was further processed to increase accuracy.

Since correcting errors of prop scar omission would have required labor and cost intensive manual delineation that were outside the scope of the project budget, it was decided that the post processing effort should focus on automated commission error removal using Classification and Regression Tree (CART) modeling within see5 software.

Feature Analyst often mis-labeled a feature as a prop scar because it was linear and bright, but wasn't actually surrounded by seagrass and was actually commission error, not a prop scar. To correct this problem, CART inputs included spectral means and standard deviations for the inside of each mapped polygon, spectral means and standard deviations for a small buffer (the "donut") around each polygon, and shape which was characterized as a normalized ratio of perimeter to area. The "donuts" gave the CART analysis a critical element of context and helped to eliminate the errors of commission by giving CART a look at the areas immediately surrounding the prop scars. CART modeling removed a major amount of commission error, reducing the number of propeller scar polygons from 217,000 to 118,000.

In the initial CART runs, the image analyst observed that a significant percentage of the polygons removed were actual prop scars. See5 lets the user assign a "cost" of mislabeling. The analyst found that by using a cost of 3 (meaning that it is 3 times more "expensive" to call an actual prop scar a non-prop scar than it is to call a non-prop scar a prop scar) achieved the best result in terms of balancing the removal of commission error with the preservation of correctly mapped scars.

F. Results

Figure 23 shows small portion of the ADS40-52 imagery alone (Figure 23a) and draped with the final propeller scar map produced from the ADS40-52 data using Feature Analyst and CART modeling with no manual editing(Figure 23b). Scattered errors of omission are evident, but can be easily captured using heads up digitizing. The automated procedures allowed the computer to classify easily identified and systematic scars, reserving expensive analyst time for the delineation of less obvious scars.

Much of Redfish Bay's shallow regions show Figure 23's same pattern of ubiquitous scarring. While propeller scars comprise less than 1% of the area of the project area, their resulting fragmentation of seagrass beds is universal.

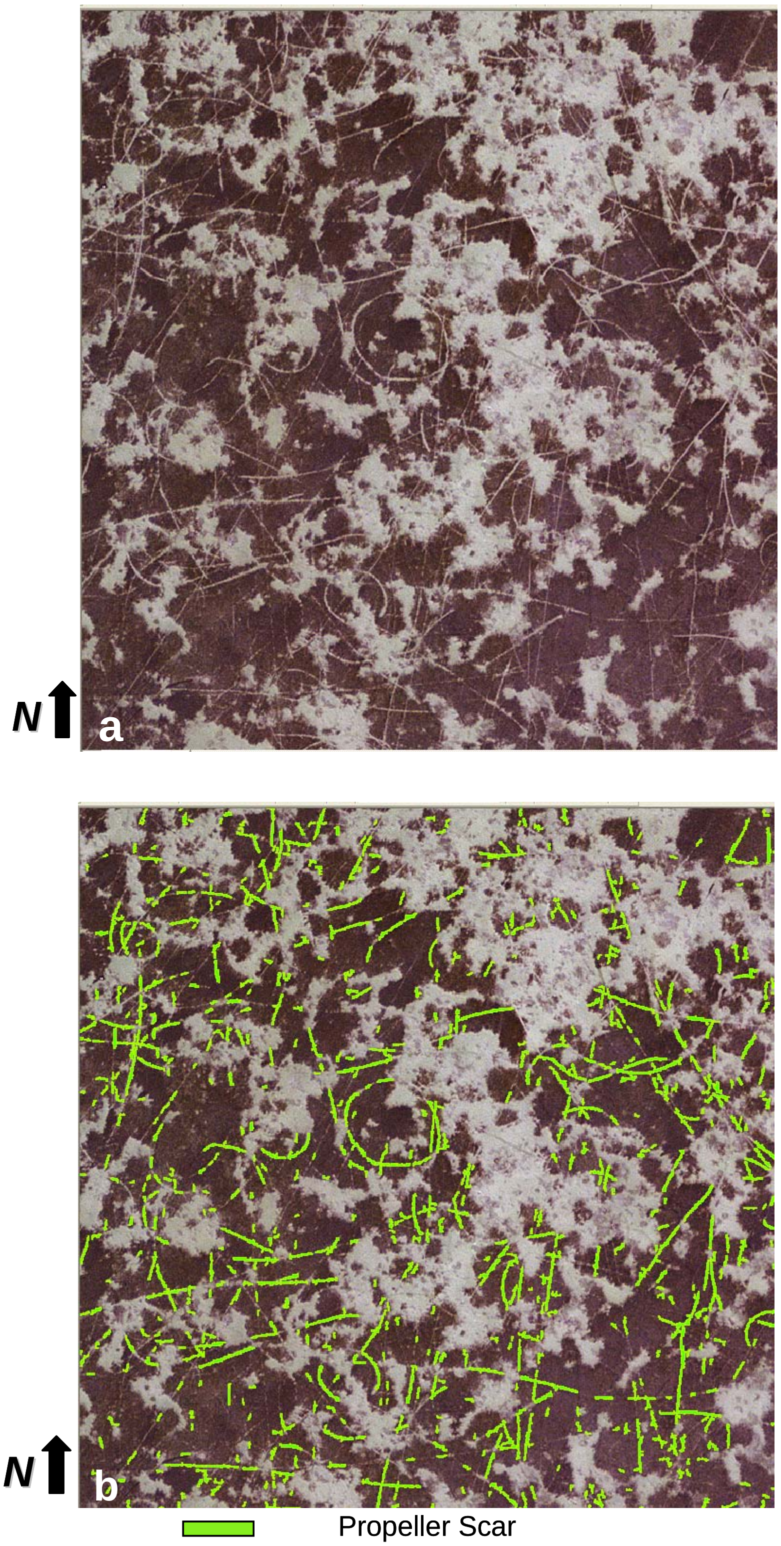

Figure 23. Natural color ADS40-52 imagery alone (a), and draped with the propeller scar map resulting from Feature Analysts and CART modeling (b).

G. Accuracy Assessment

Tables 5 through 8 present the error matrices of the totally automated prop scar maps created from

- ADS40-52 data classified first with Feature Analyst and then post-processed with CART to remove errors of commission,
- ADS40-52 data classified only with Feature Analyst,
- DMC data classified only with Feature Analyst, and
- UltraCam data classified only with Feature Analyst.

The prop scar maps are two class maps with areas classed as either prop scar or not prop scar. Therefore the error matrices are simple two class matrices. However, it was common for a prop scar reference site to encompass areas mapped only partially as prop scar which made creating a map label for the site problematic. Because the goal of the totally automated prop scar map is to indicate where a prop scar might be and, thus, serve as a precursor to eventual manually editing, we chose to apply the prop scar map label if as little as 1 percent of the site was mapped as prop scar. To understand the impact of this decision we created subclasses within the prop scar class of 1-20% prop scar, 21-40% prop scar, 14-60% prop scar, and 61-100% prop scar. Each error matrix shows (in grey) the number of prop scar map accuracy assessment polygons receiving each subclass label.

Analysis of the error matrices indicates the following:

- The prop scar maps produced with the ADS52 data are substantially better (85% overall accuracy) than the maps produced from the DMC or UltraCam data (76% and 60% overall accuracy, respectively). Kappa analysis of the matrices indicates that
    - The maps created from the ADS40-52 data are significantly better than the maps created from the DMC data at the 90% level, and from the UltraCam data at the 95% level.
    - Additionally, the maps created from the DMC data are significantly better than the maps created from the UltraCam data at the 95% level.
- None of the matrices show errors of commission of “not prop scar” to “prop scar”. However, cursory manual inspection of the maps showed that this type of

error existed to an unacceptable level in the three maps created with only Feature Analyst processing[7]. For this reason, CART post processing was run on the ADS52 Feature Analyst map to minimize these errors of commission. Even though the CART modeling resulted in a map which showed significant reduction in prop scar commission errors, the resulting error matrix does not reflect this increase in accuracy because propeller scars are a rare event, comprising less that 1% of the mapped area. Therefore, the probability of a 50 site random sample selecting a "not prop scar" area which was erroneously mapped as prop scar is very low.

Table 5. Error matrix for the propeller scar map created from ADS40-52data using Feature Analyst and CART.

			Reference		
		no prop scar	prop scar	Total	Comsumer's Accuracy
	no prop scar	52	32	84	62%
	prop scar	0	123	123	100%
Map	1-20% prop scar	0	15		
	21-40% prop scar	0	20		
	41-60% prop scar	0	22		
	61-100% prop scar	0	66		
	Total	52	155	207	
	Producer's Accuracy	100%	79%	Overall Accuracy	85%

Table 6. Error matrix for the propeller scar map created from ADS40-52data using Feature Analyst only.

			Reference		
		no prop scar	prop scar	Total	Comsumer's Accuracy
	no prop scar	52	31	83	63%
	prop scar	0	124	124	100%
Map	1-20% prop scar	0	16		
	21-40% prop scar	0	20		
	41-60% prop scar	0	22		
	61-100% prop scar	0	66		
	Total	52	155	207	
	Producer's Accuracy	100%	80%	Overall Accuracy	85%

[7] In fact, the reason the CART post-processing was run on the ADS40-52 Feature Analyst map was to minimize these errors of commission.

Table 7. Error matrix for the propeller scar map created from DMC data using Feature Analyst only.

			Reference		
		no prop scar	prop scar	Total	Comsumer's Accuracy
	no prop scar	52	49	101	51%
	prop scar	0	106	106	100%
Map	1-20% prop scar	0	21		
	21-40% prop scar	0	18		
	41-60% prop scar	0	17		
	61-100% prop scar	0	50		
	Total	52	155	207	
	Producer's Accuracy	100%	68%	Overall Accuracy	76%

Table 8. Error matrix for the propeller scar map created from UltraCam data using Feature Analyst only.

			Reference		
		no prop scar	prop scar	Total	Comsumer's Accuracy
	no prop scar	52	82	134	39%
	prop scar	0	73	73	100%
Map	1-20% prop scar	0	16		
	21-40% prop scar	0	17		
	41-60% prop scar	0	15		
	61-100% prop scar	0	25		
	Total	52	155	207	
	Producer's Accuracy	100%	47%	Overall Accuracy	60%

V. Findings and Conclusions

This project was very complex, requiring the coordination of personnel and resources from multiple organizations. That all three image sets were collected on the same day is amazing and speaks volumes to the commitment of NOAA, the operators, and the Texas Parks and Wildlife Department. This analysis and review suggest the following findings and conclusions:

- Digital airborne UltraCam, ADS40-52, and DMC imagery can be used successfully to map benthic habitat types and propeller scars.
- In shallow water, the infrared band is an important discriminator among benthic classes and between benthic habitat classes and propeller scars..
- Propeller scars comprise less than 1% of the area of Redfish Bay, but are ubiquitous throughout the shallow areas of the Bay, significantly fragmenting seagrass beds.
- Automated image classification of ADS40-52 imagery, relying on Feature Analyst augmented with CART modeling, can be used to successfully identify

and map the majority of propeller scars in seagrass beds. Mapping of every single scar requires supplemental manual digitizing.

- The three image data sets were collected under almost identical weather and tidal conditions, indicating that differences between image sets and maps created from them are most likely due to differences in the sensors and in any processing applied to the imagery.
- Submerged targets at 1, 1.5, and 2 meter depths were visible and the target patterns were distinguishable in all three image sets.
- All reviewers found all three image data sets to be suitable for benthic habitat and propeller scar mapping. However, significant inconsistency between the reviewer's opinions made it impossible to use the qualitative reviews to rank the quality of the systems against one another.
- Quantitative analysis points to some significant differences between the image data sets.
    - The spatial accuracy of all three sensors greatly exceeded contract standards with the DMC having the highest spatial accuracy.
    - Spectral separatability of benthic habitat classes and propeller scars is best in the DMC and the ADS40-52 imagery.
    - Propeller scar maps produced from the automated classification of the ADS40-52 imagery were significantly more accurate than those produced from the DMC or UltraCam imagery; and propeller maps produced from automated classification of the DMC imagery are significantly more accurate than those produced from the UltraCam imagery.

We believe that the ADS40-52 higher propeller scar map accuracy results from the system's higher multispectral spatial resolution, and from the spectral fidelity of its multispectral bands. The map accuracy results point to the choice of the ADS40-52 for propeller scar mapping. While the DMC had the highest spatial accuracy of the image data sets, all of the data sets exceeded NOAA's spatial accuracy requirements, leaving the choice of what system to use to be determined by the map with the highest thematic accuracy.

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